Towards the controlled formation of antiprotonic atoms

Dr. Fredrik Parnefjord Gustafsson
On behalf of the AEgIS Collaboration
12-June-2024

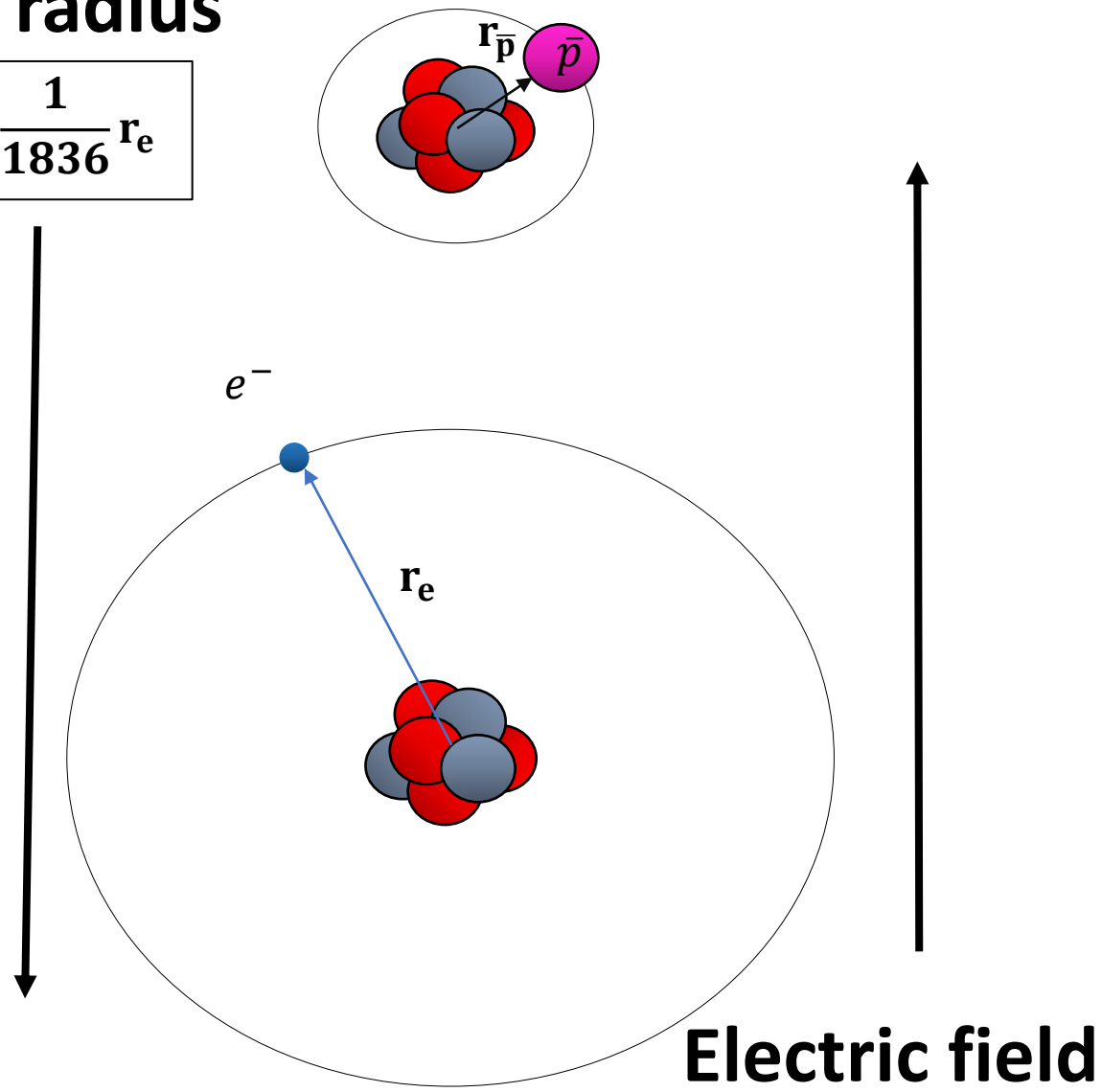
PSAS'2024

The antiprotonic atom

- Antiproton is a stable negatively charged hadron 1836x heavier than the electron.
- Antiprotonic atoms form deeply bound states near the nucleus.
- <u>Sensitive laboratory for benchmarking both QED and QCD.</u>

Bohr radius

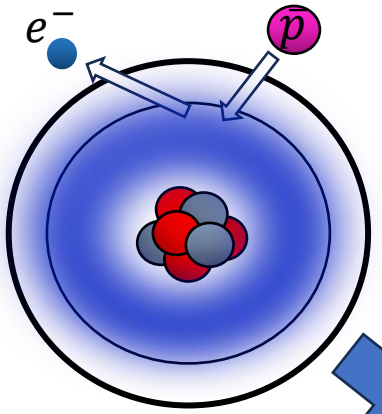
$$\mathbf{r_{\bar{p}} \sim \frac{1}{1836} r_e}$$



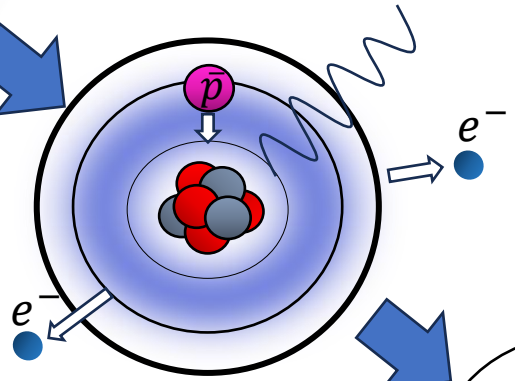
The life of an antiprotonic atom

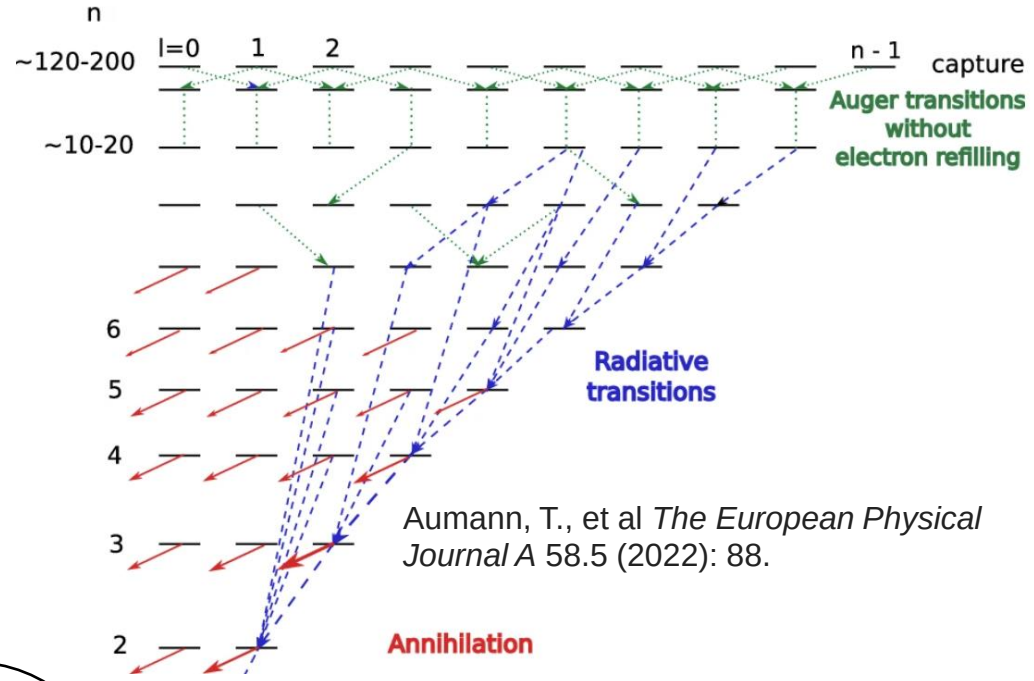
Capture of the antiproton in a **high-n Rydberg state**.

$$n_{\bar{p}} \sim \sqrt{\frac{m_{\bar{p}}}{m_e}} n_e \sim 40 n_e$$



Cascade emitting x-rays and Auger electrons.

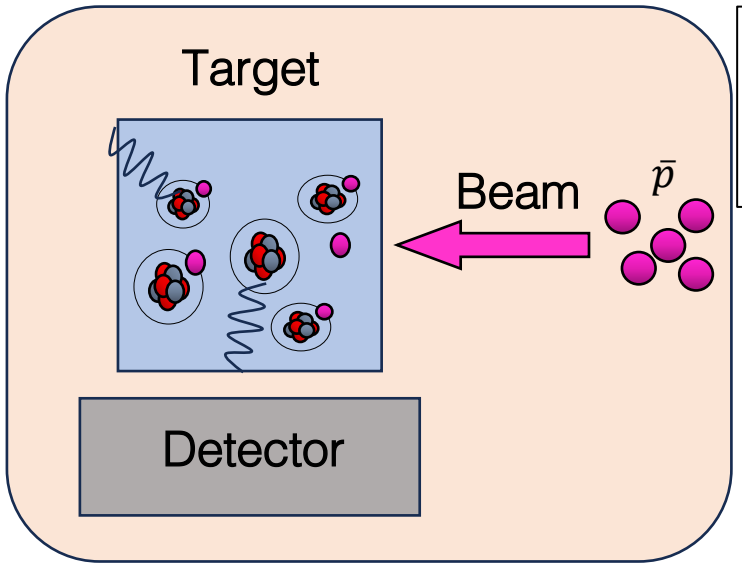




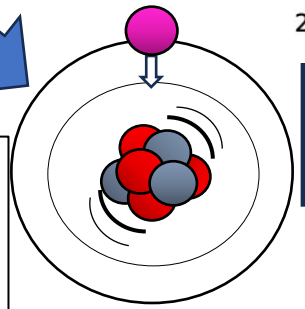
Aumann, T., et al *The European Physical Journal A* 58.5 (2022): 88.

Spin-flip-induced quadrupole resonance in odd-A exotic atoms
Fredrik P. Gustafsson, Daniel Pęcak, and Tomasz Sowiński
Accepted 2 May 2024
Accepted in PRC

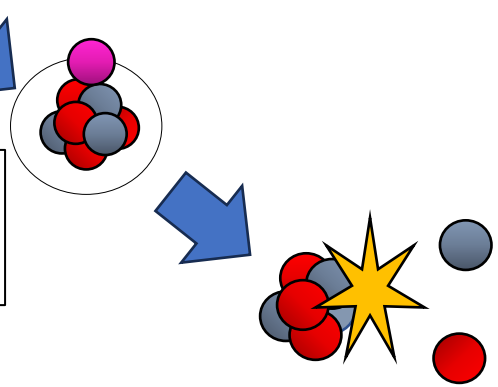
Typical experiment:



Antiproton approaching stripped nucleus, **strong interaction influences orbitals**. Resonance effects can take place.

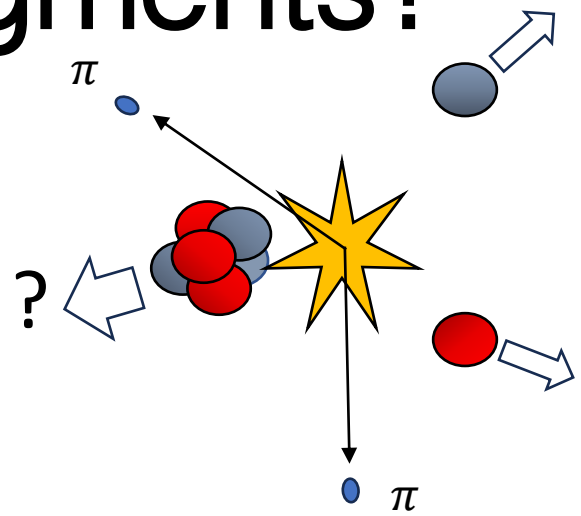


Linebroadening caused by **annihilation with nuclear perifery**.



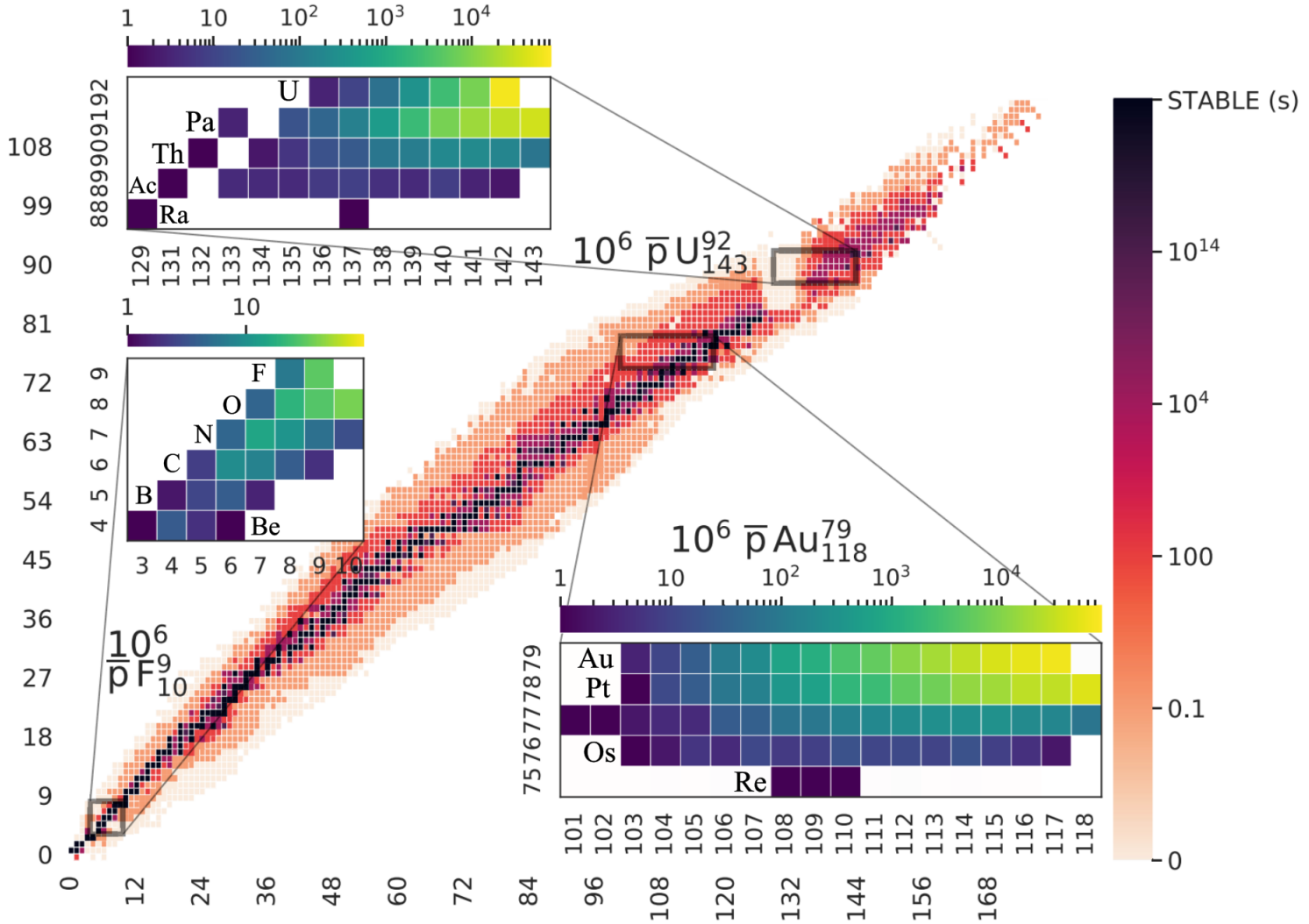
Annihilation on nucleus

What about the resulting nuclear fragments?



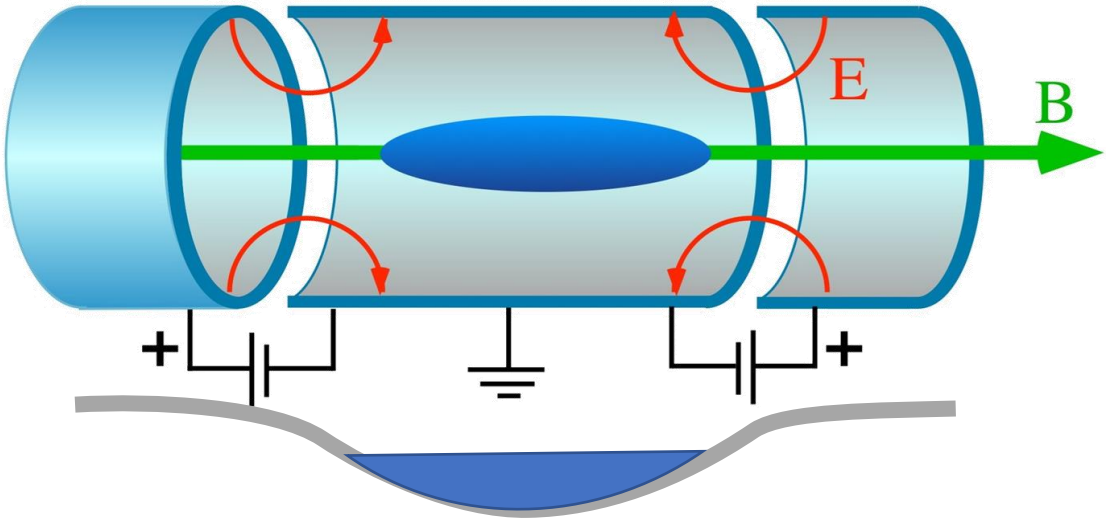
- Nuclear fragments are (often) radioactive Highly Charged Ions (HCI)
- <u>Sensitive probes for:</u>
  - QED
  - Weak interaction
  - Nuclear structure
- GEANT4/FLUKA simulations of fragments formed from 1 million Pbar annihilations:

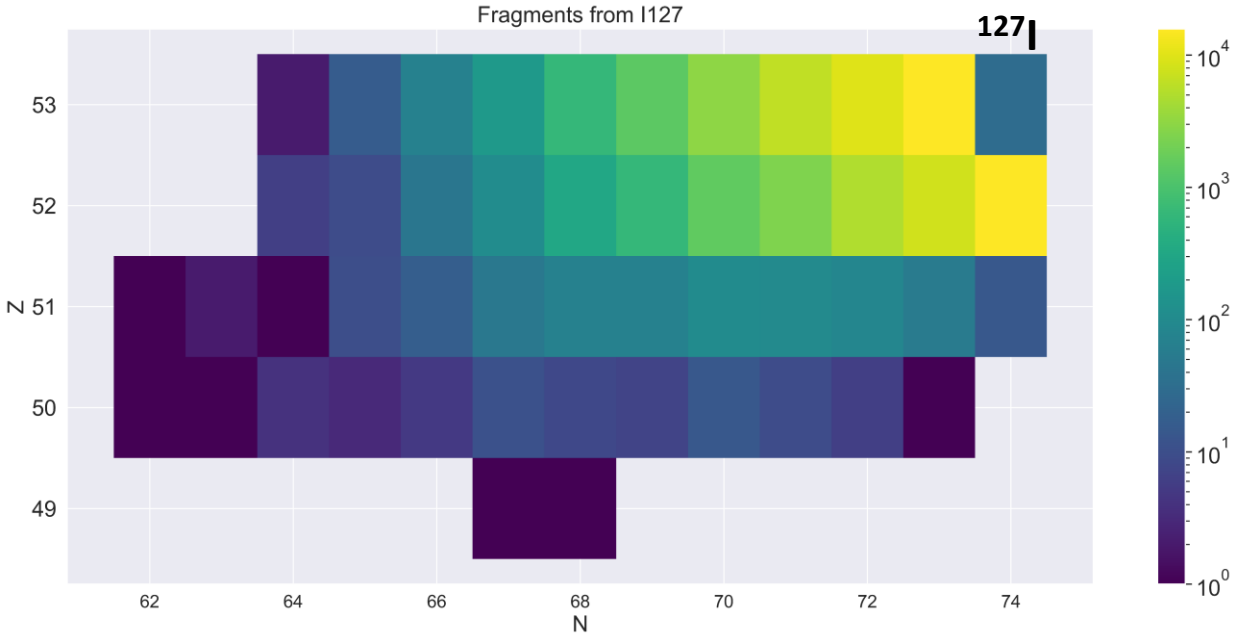
G. Kornakov et al., PRC 107, 034314 (2023)

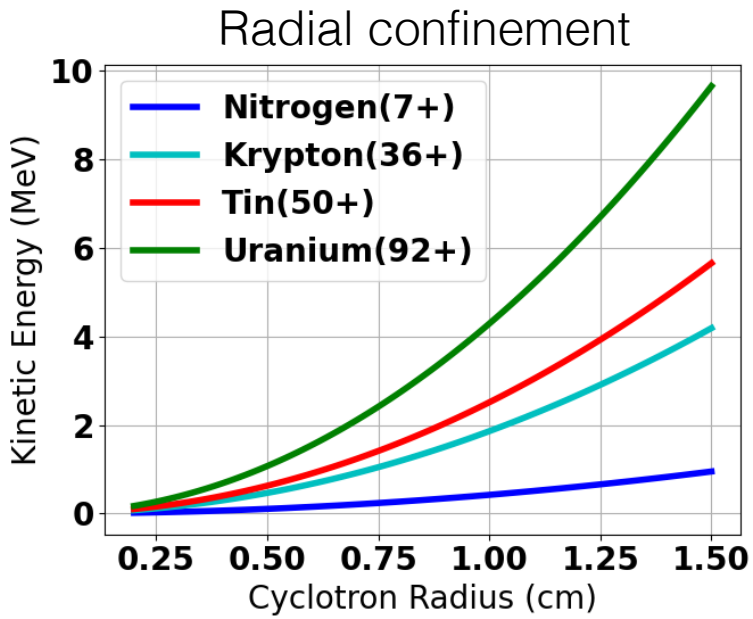


Can we trap fragments in a Penning-Malmberg trap?

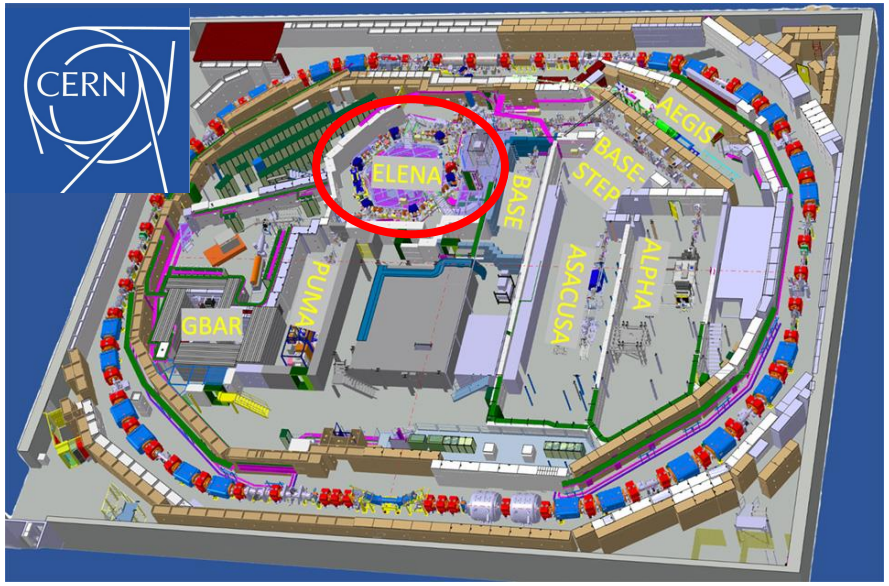
- Trapping fractions of nuclear fragments determined by charge state (q), E and B-field:
- Axial confinement by electrode potential (~10kV)
- Radial confinement by B-field (5T)
- Trapping fraction enhanced by charge state. >50% trapped at 10 keV/q

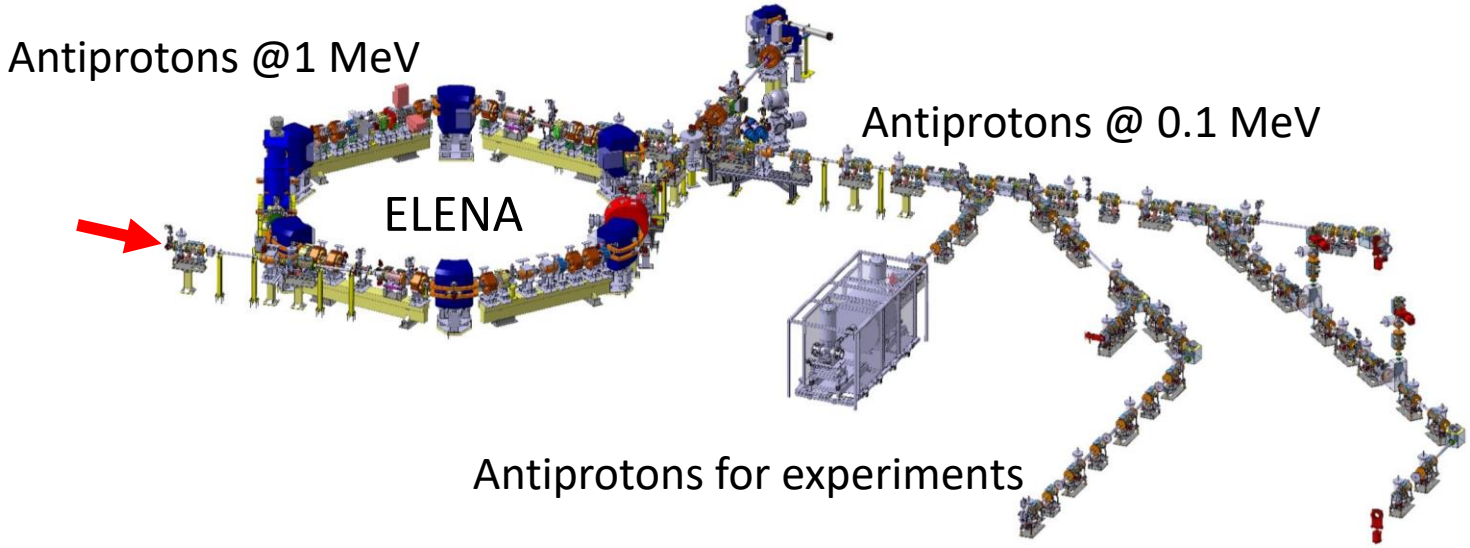






Experiements at the Antimatter factory





ALPHA

Trap
Antihydrogen trapping
Spectroscopy
Gravity

ASACUSA

Beam
Antiprotonic atoms
Collisions
Antihydrogen
Spectroscopy

AEGIS

Beam
Pulsed production
of antihydrogen
Gravity
Positronium
Antiprotonic atoms+HCIs

BASE

Trap
Mass spectroscopy
$\bar{p}$ magnetic moment

GBAR

Trap
Antimatter gravity
Lamb-shift

PUMA

Movable trap
for antiprotons
Study of exotic nuclei

AEgIS

- Goal: Forming a cold beam of $\bar{H}$ and measure its trajectory in a gravitational field to <1% accuracy.
- Pulsed production of $\bar{H}$ achieved using laser excited Rydberg positronium ($\sigma \propto n^4$)
- Record antiproton catching efficiency.

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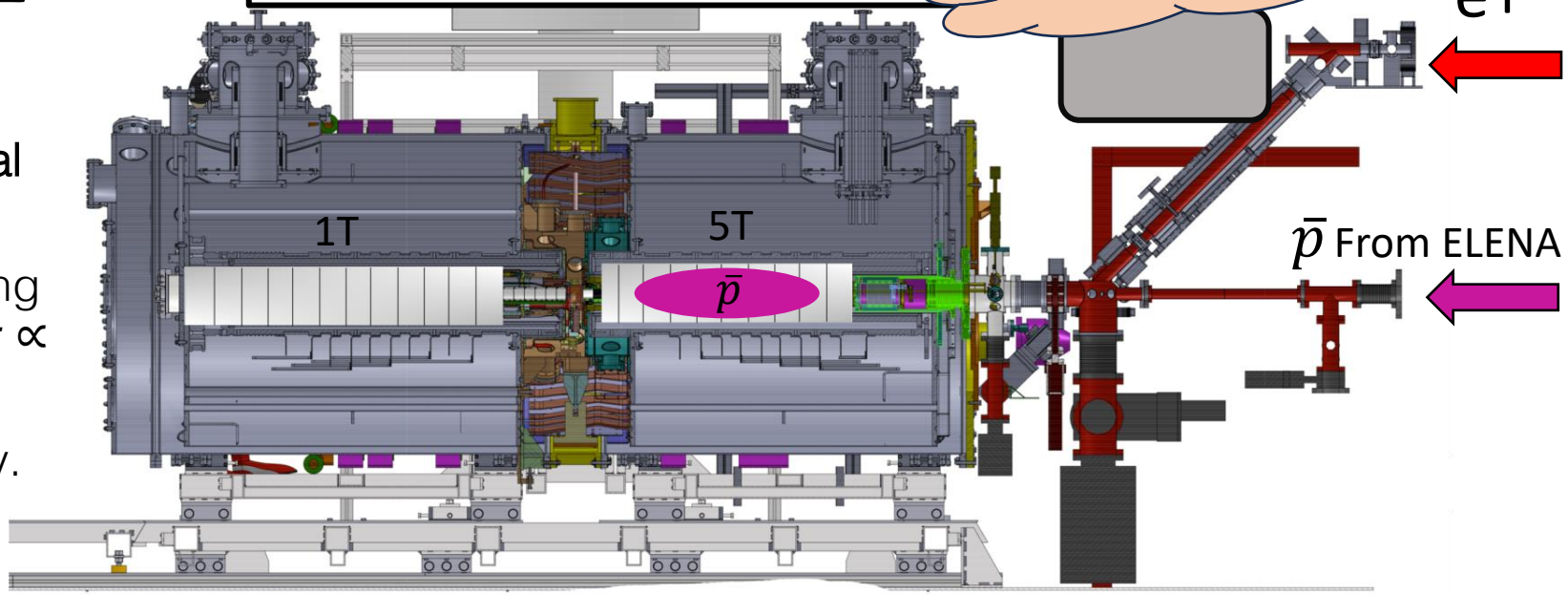
Positronium Laser Cooling via the 1^3S–2^3P Transition with a Broadband Laser Pulse

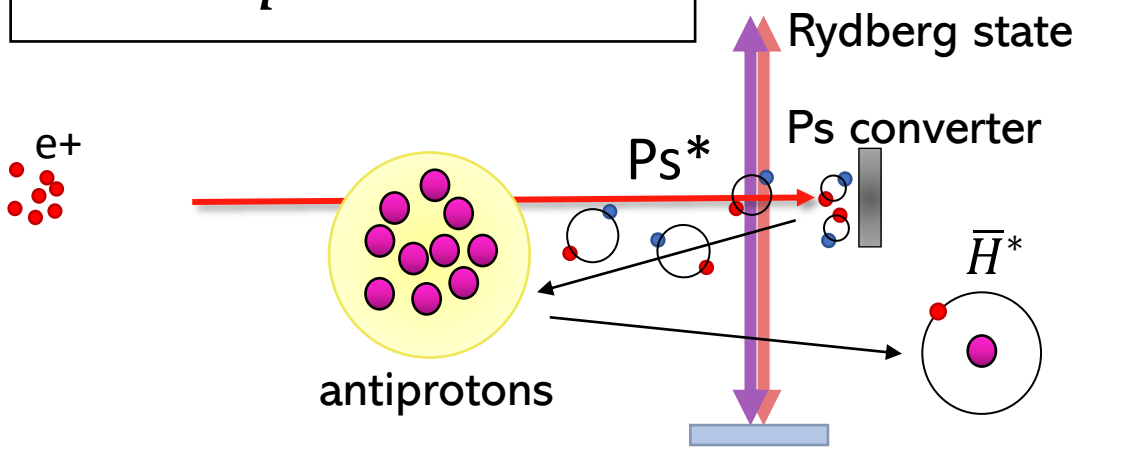
L. T. Glöggler *et al.* (AEgIS Collaboration)
Phys. Rev. Lett. **132**, 083402 – Published 22 February 2024

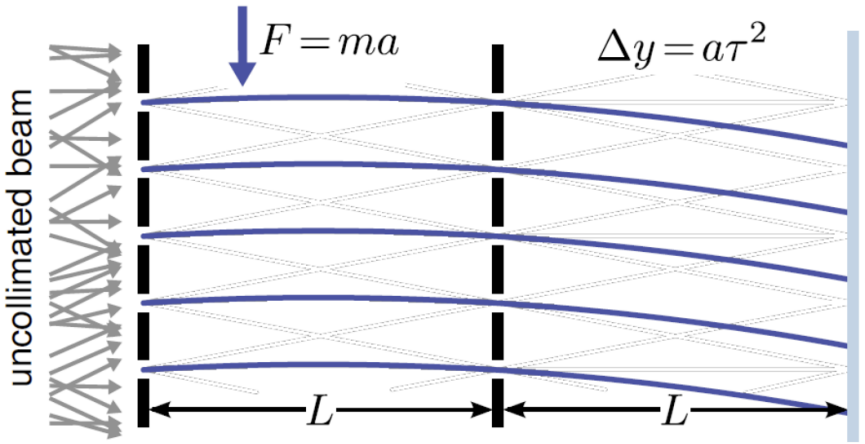
Talk by Benjamin tomorrow



Charge exchange reaction:

$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$



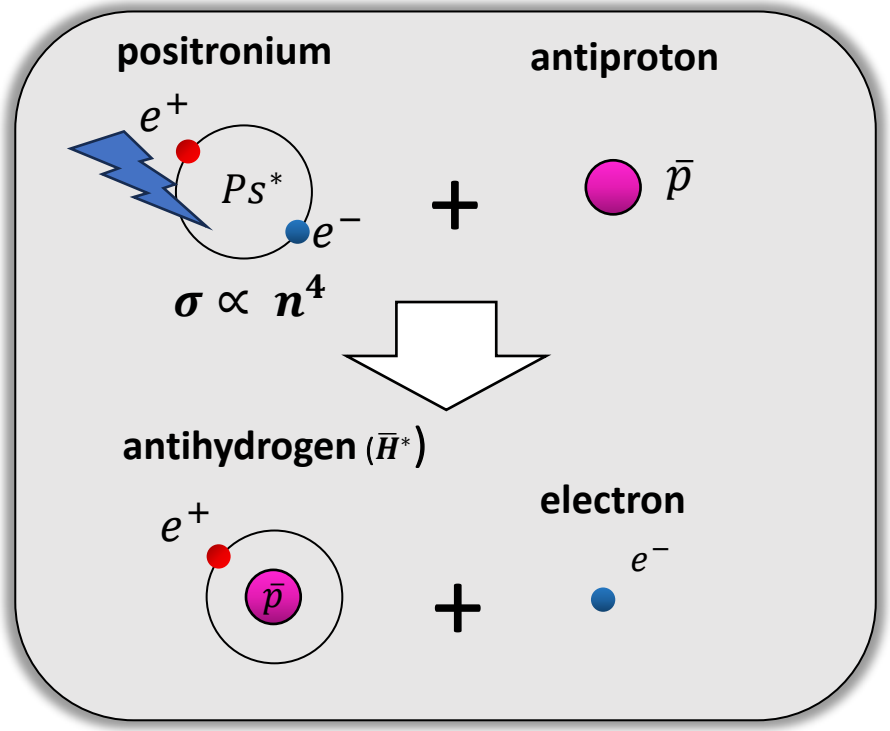


High resolution CMOS Sensor

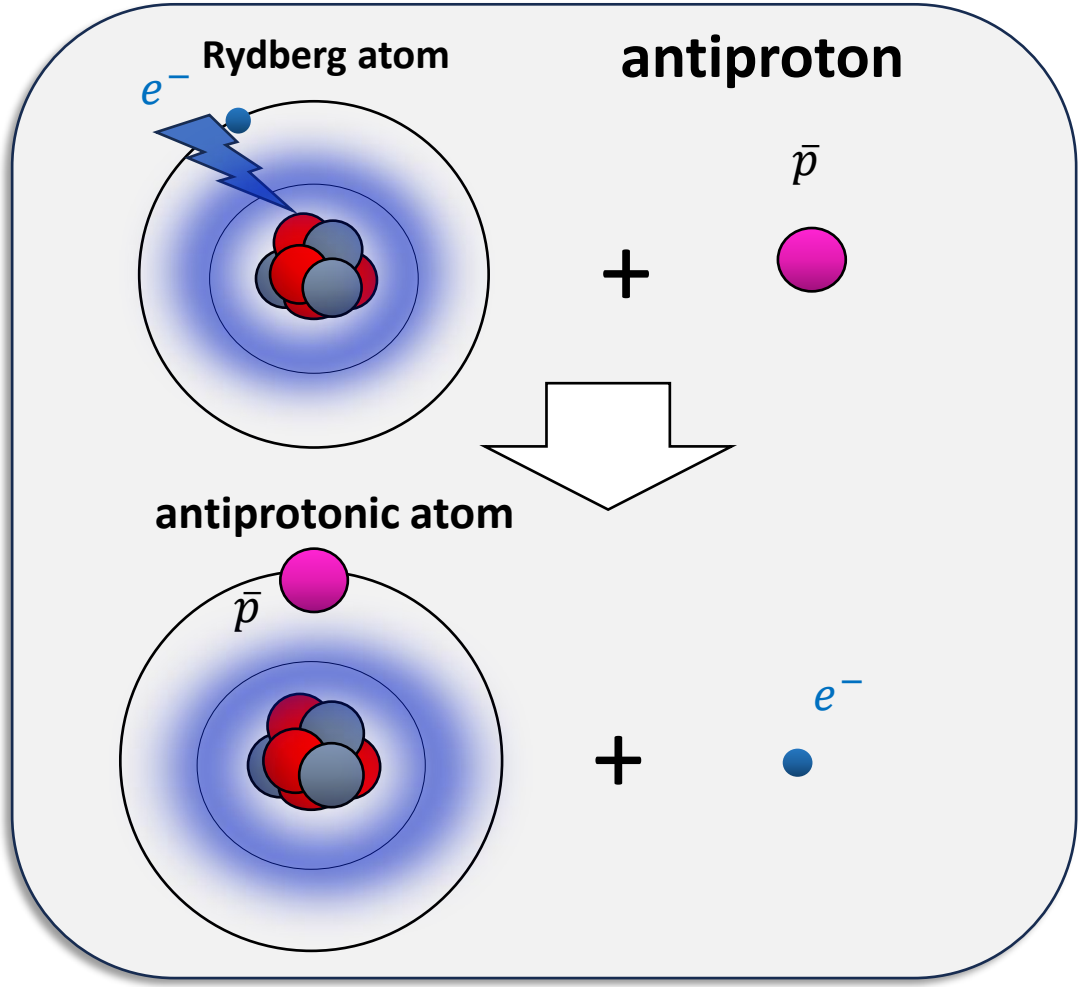
Controlled synthesis of antiprotonic atoms using charge-exchange

Charge exchange reaction:

$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$

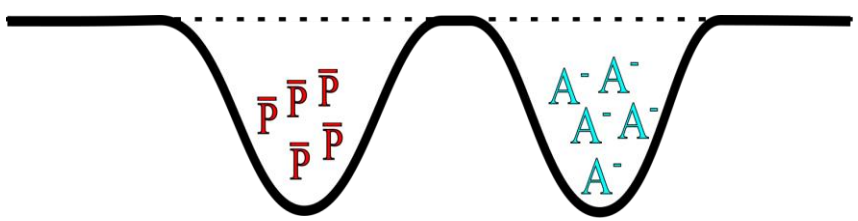


Charge-exchange with Rydberg atom

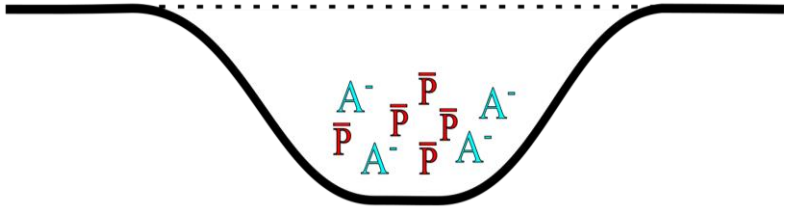


Controlled synthesis of antiprotonic atoms

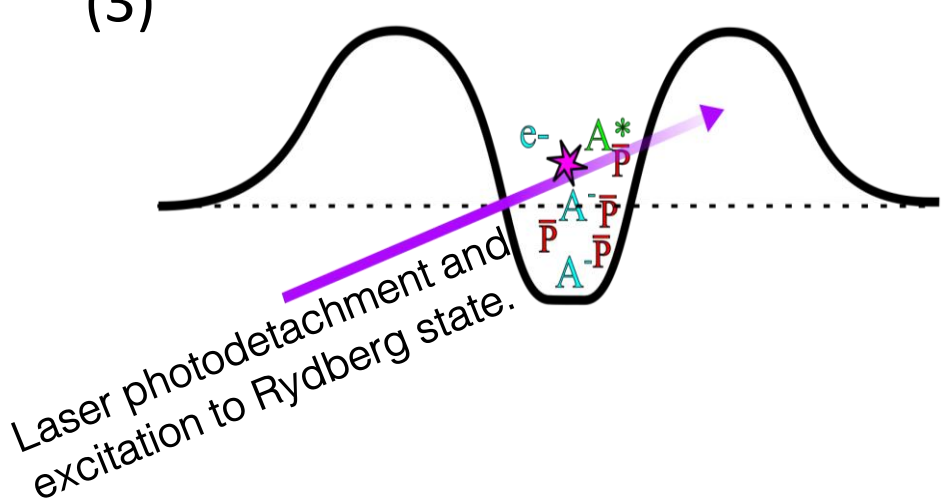
(1) Cotrapping of anions and antiprotons cooled using electrons.

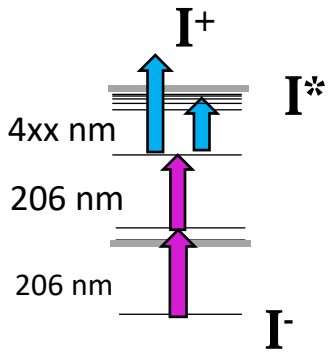


(2) Mixing anions with antiprotons.



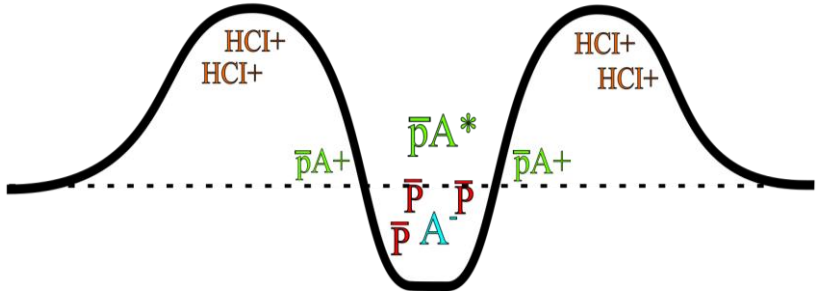
(3) Nested trap is created.



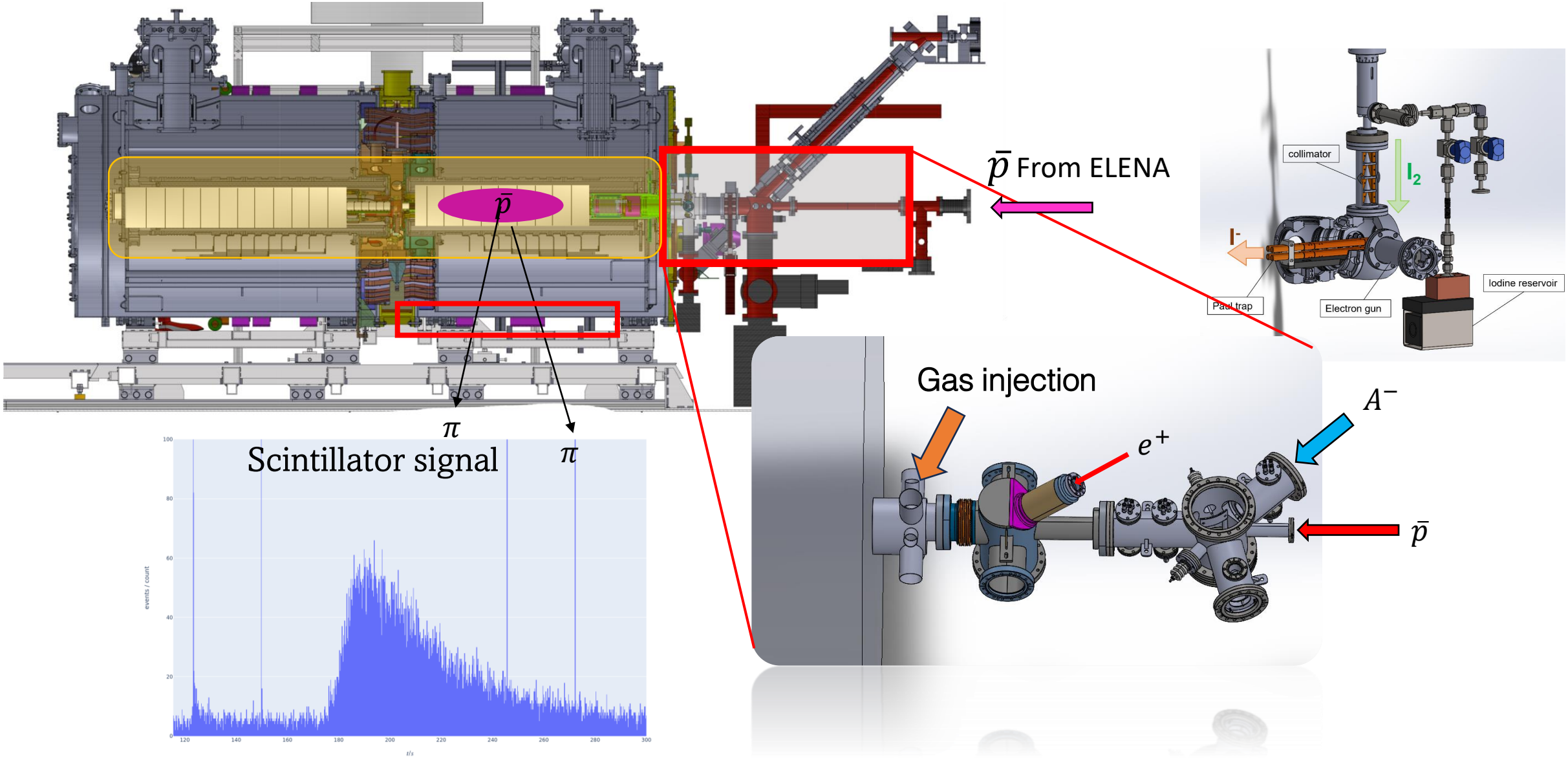


EA=3.1 eV

(4) Capture of HCl fragments after annihilation.

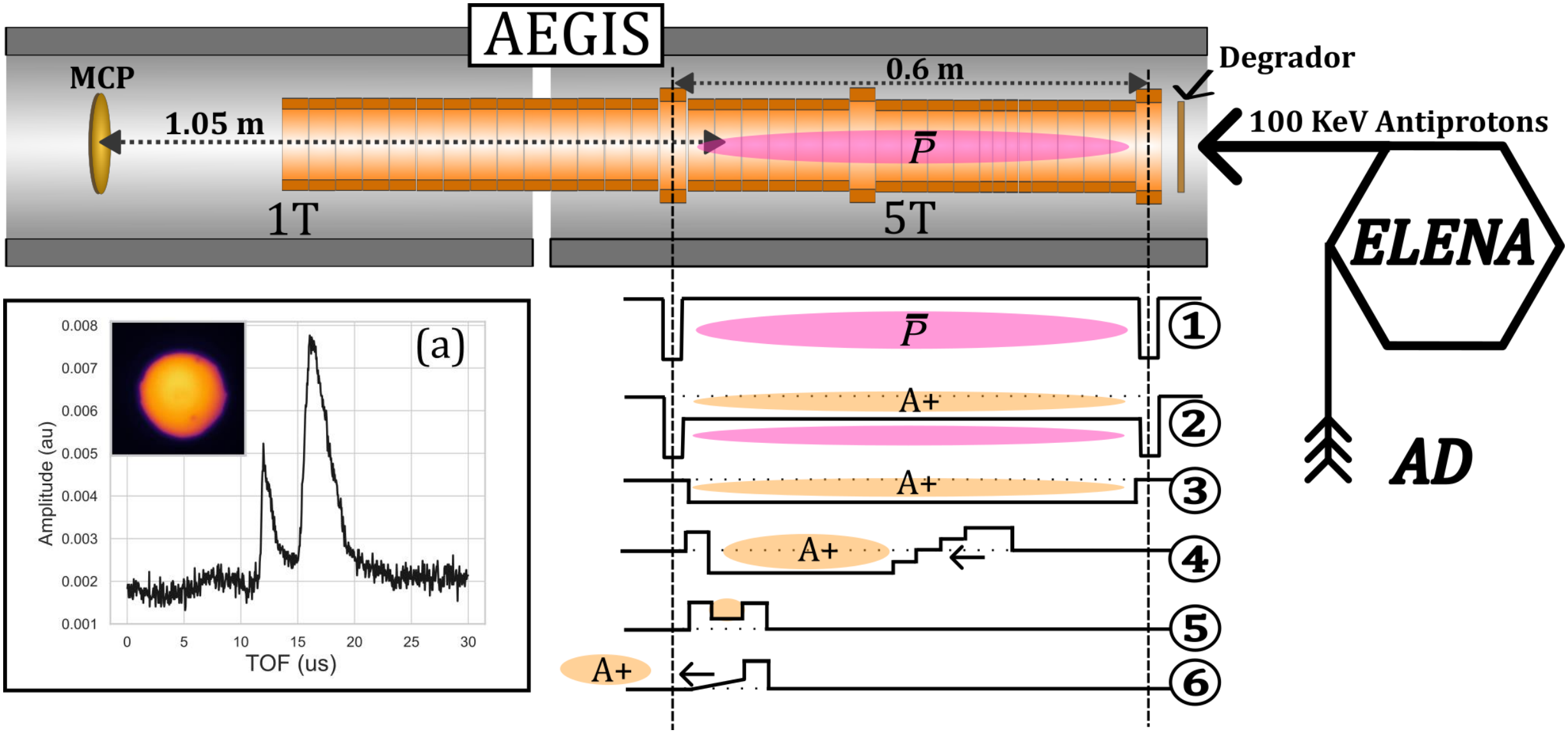


Towards the synthesis of antiprotonic atoms



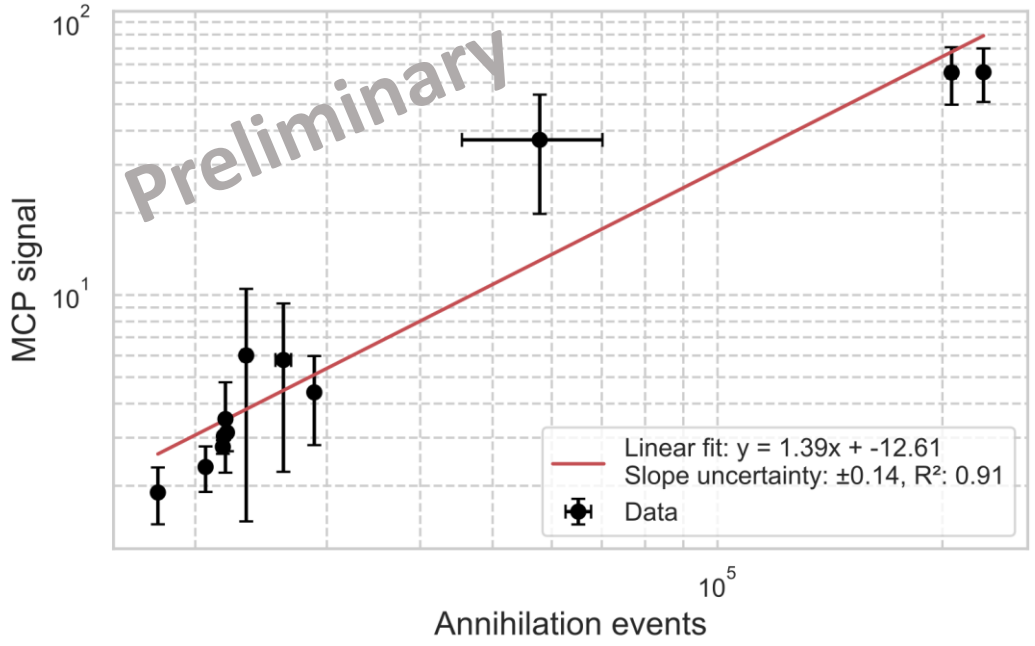
Studying positive ions formed from annihilations with nitrogen in UHV (<1e-8 mbar)

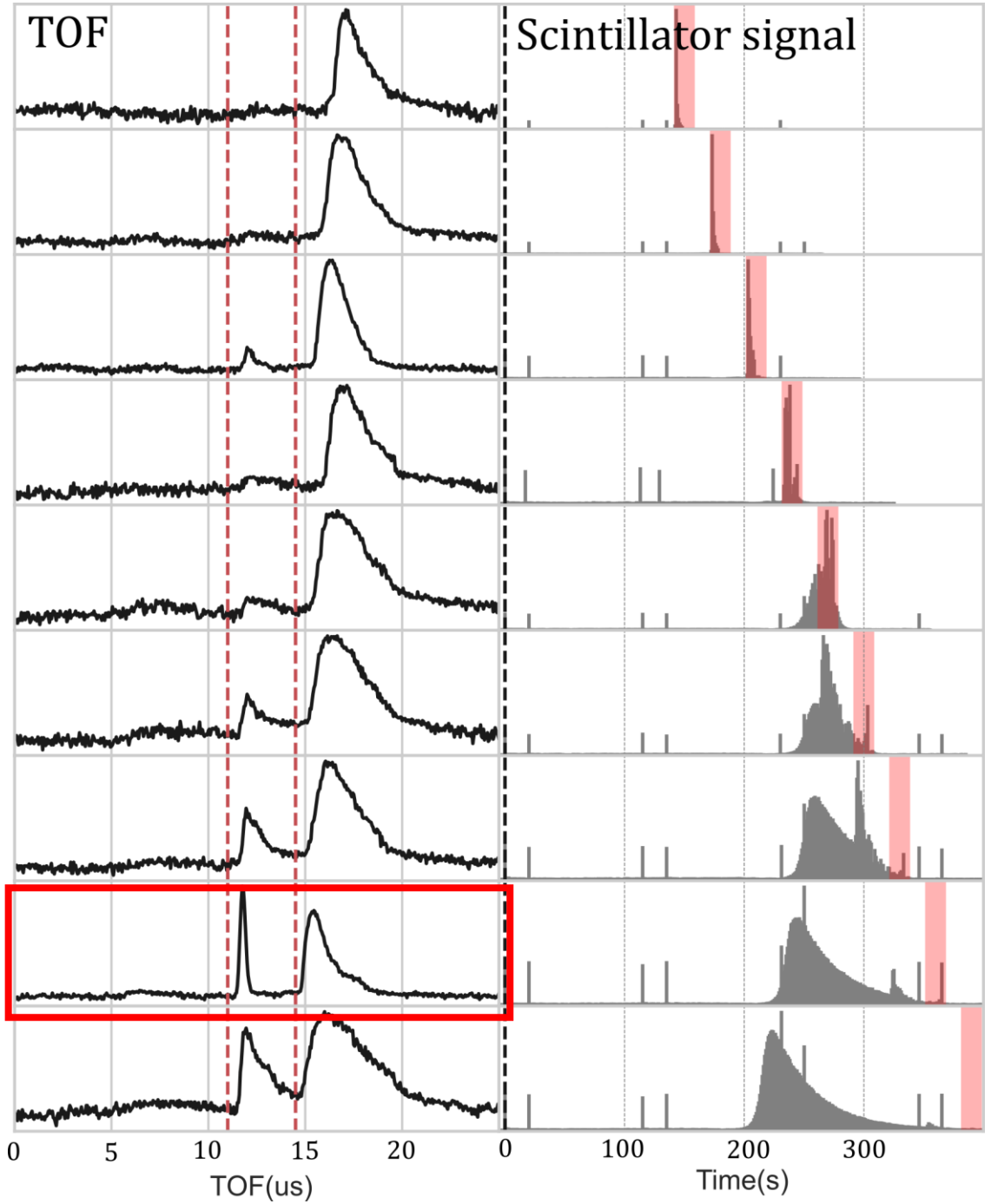
Overview of the ion capture and TOF procedure



TOF spectrum vs scintillator signal

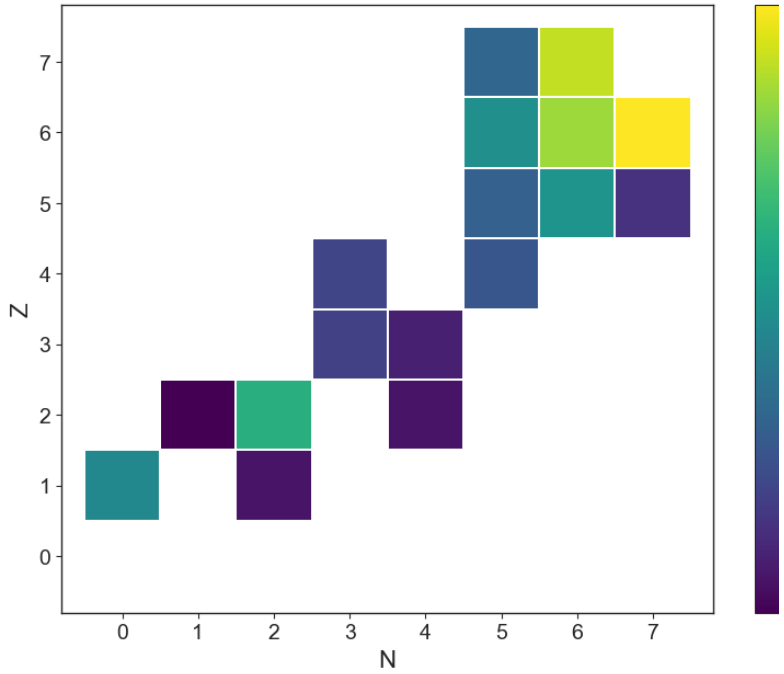
- Observation of a TOF signal formed from antiproton annihilation with nitrogen.
- Signal observed for low energy antiprotons **<1 keV**.

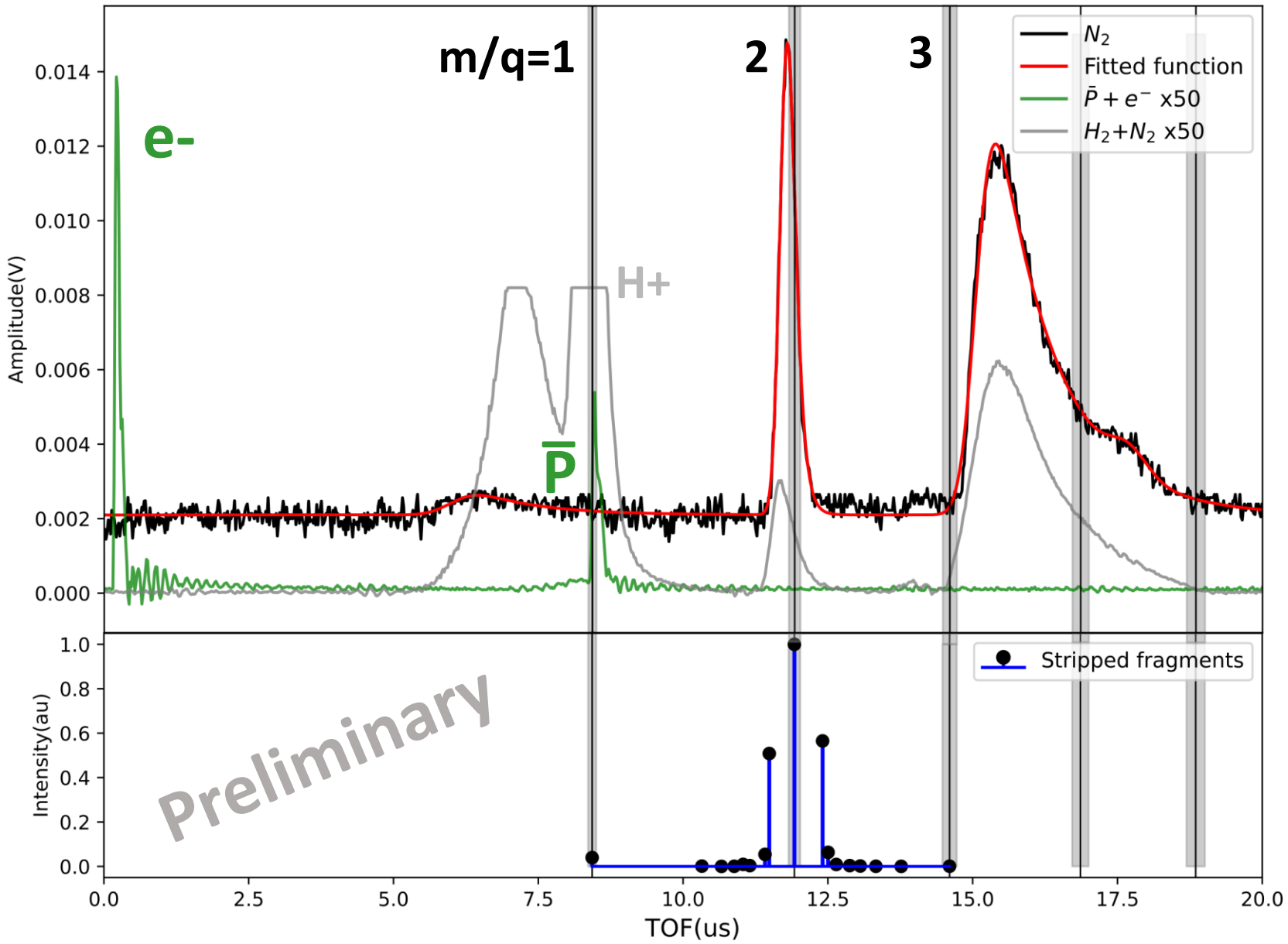




Identification of trapped HCIs formed from antiproton annihilation

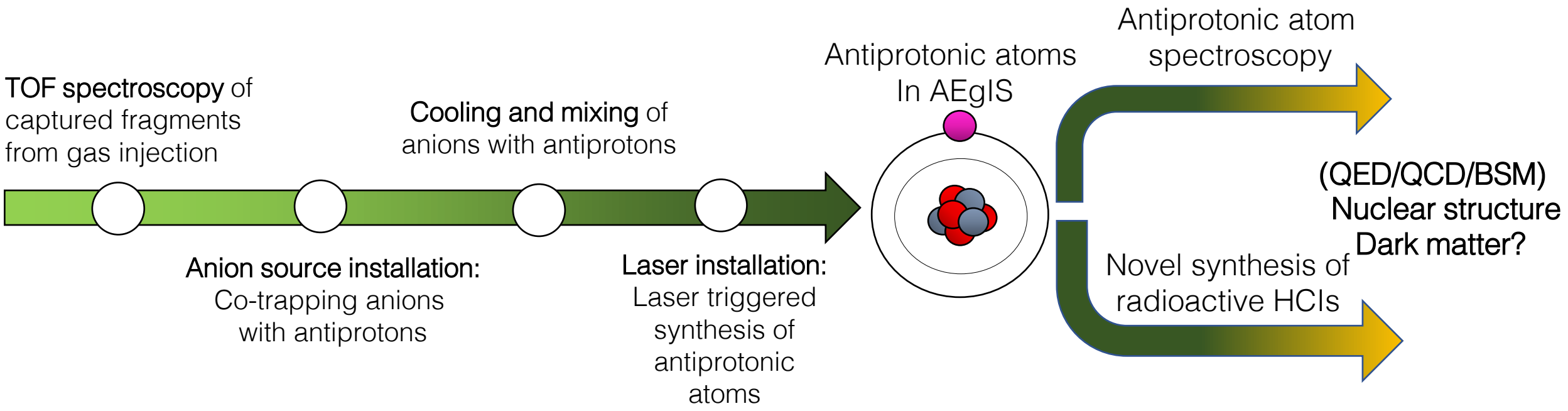
- TOF spectrum calibrated using e-, $\bar{p}$ and H^+.
- HCI trapped with m/q=2.0(1)
- Expected fragments from GEANT4 simulations: ($^{14}N^{7+}$) ,$^{12}C^{6+}$, $^{10}B^{5+}$, $^{6}Li^{3+}$, $^{4}He^{2+}$,..





Summary and outlook:

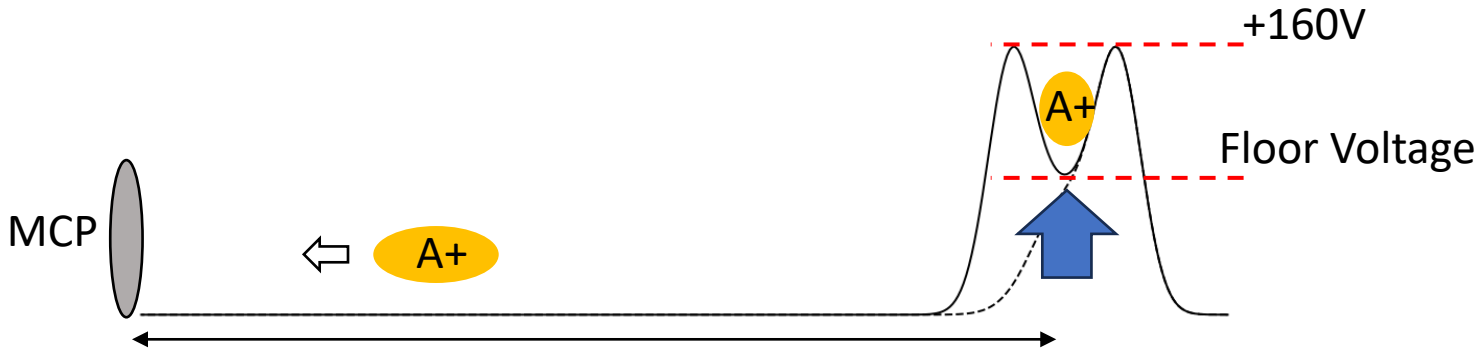
- New program at AEgIS focusing on the controlled synthesis and study of antiprotonic atoms and HCIs.
- Procedure developed at AEgIS for trapping and identifying HCIs formed from annihilation with antiprotons on atoms in UHV.
- Simulations ongoing to better understand formation mechanism.
- Planned study of HCI fragments formed from noble gases (Ar, Kr…).



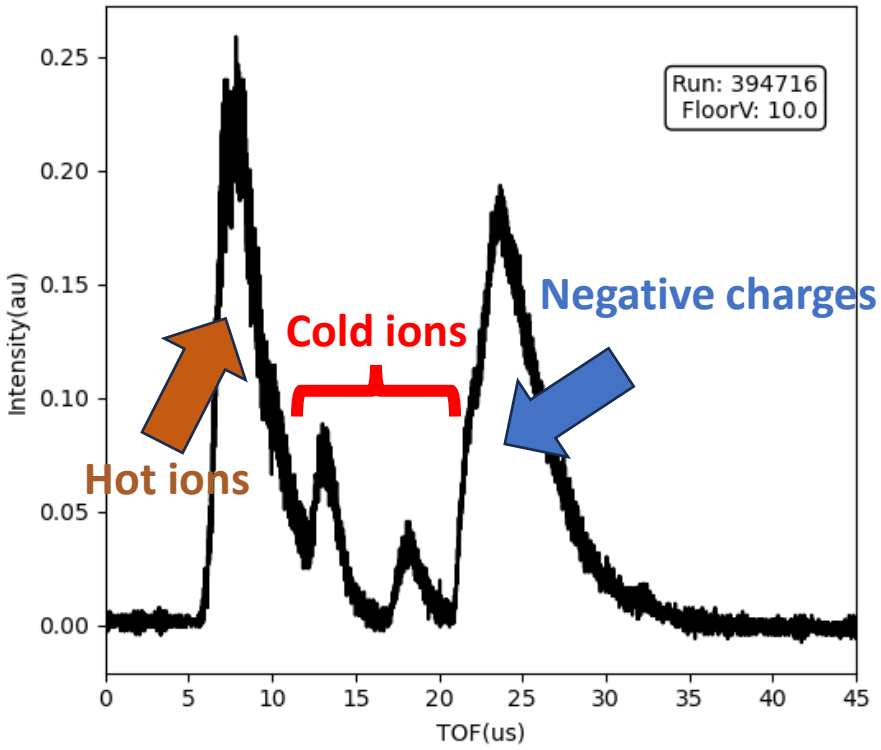
Thank you for your attention

On behalf of the AEGIS collaboration

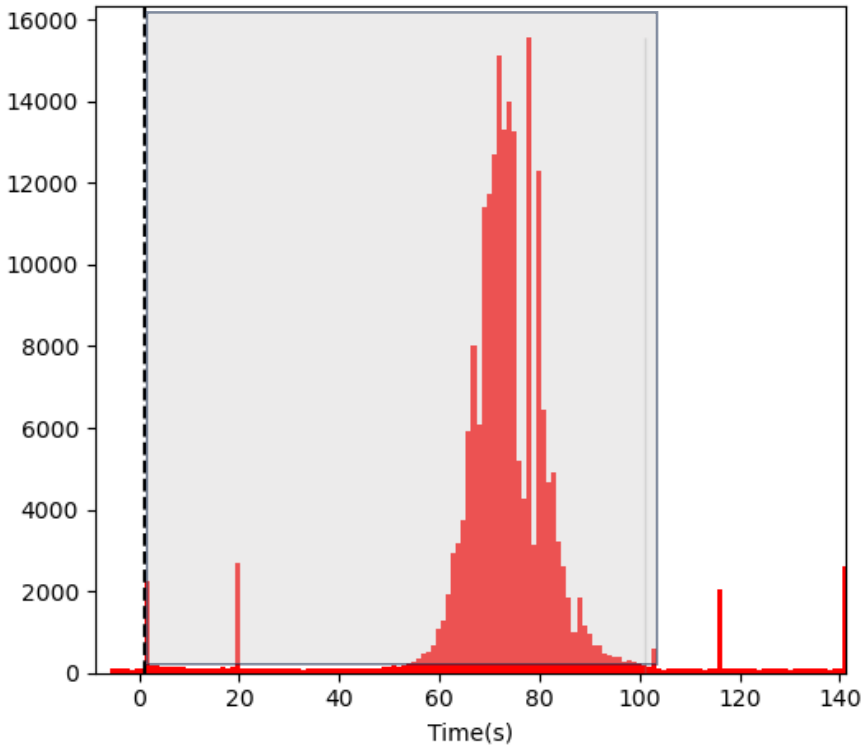
Sample data during campaign

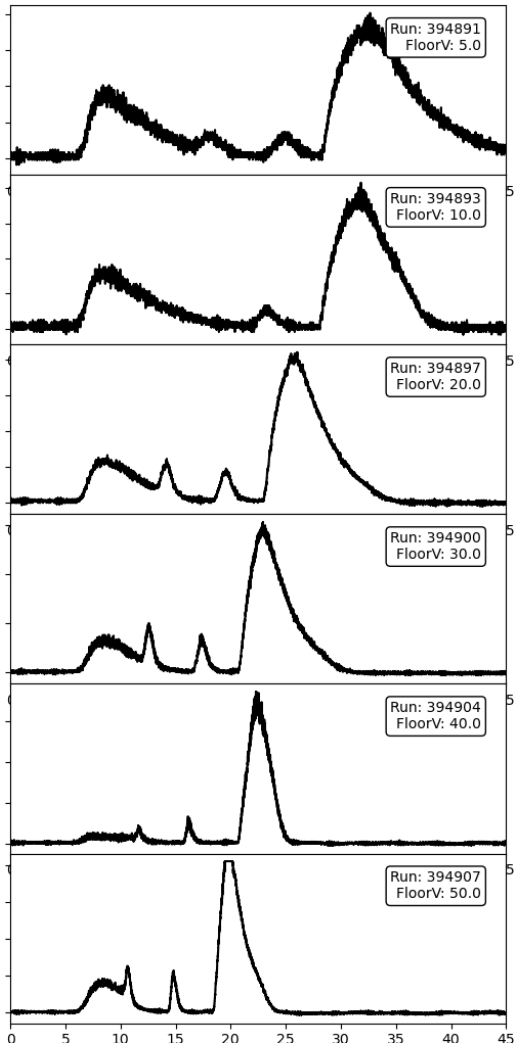


MCP TOF signal



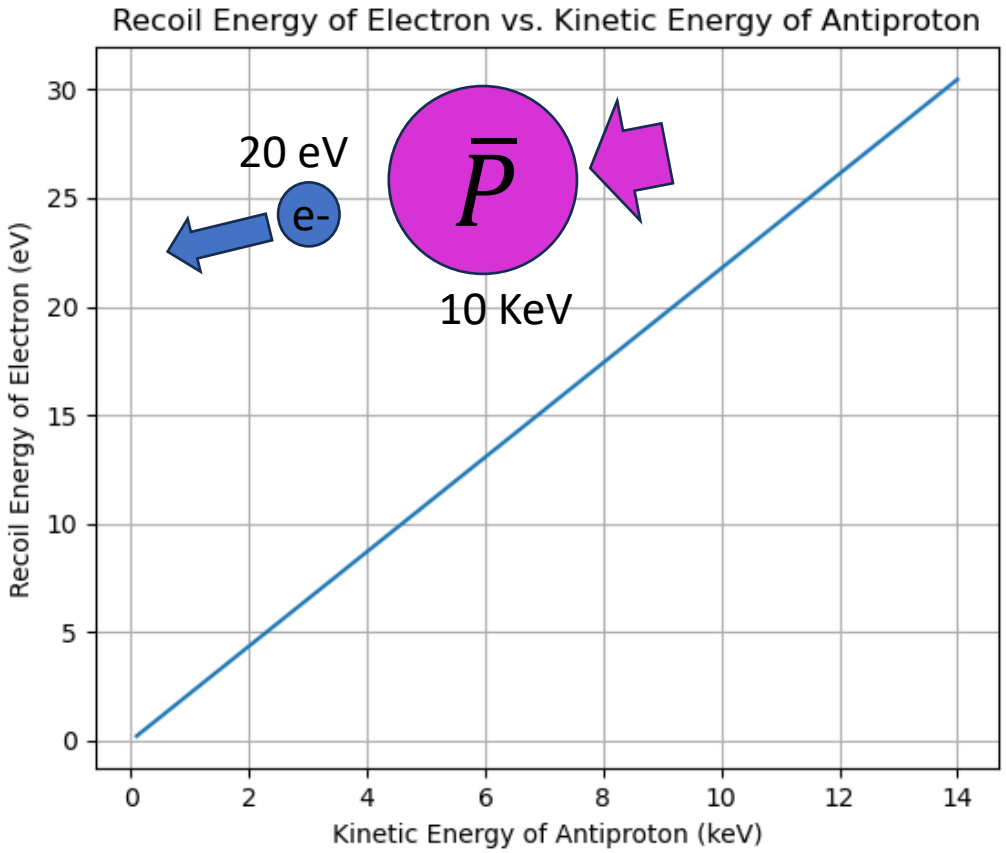
Scintillator signal (SC21)

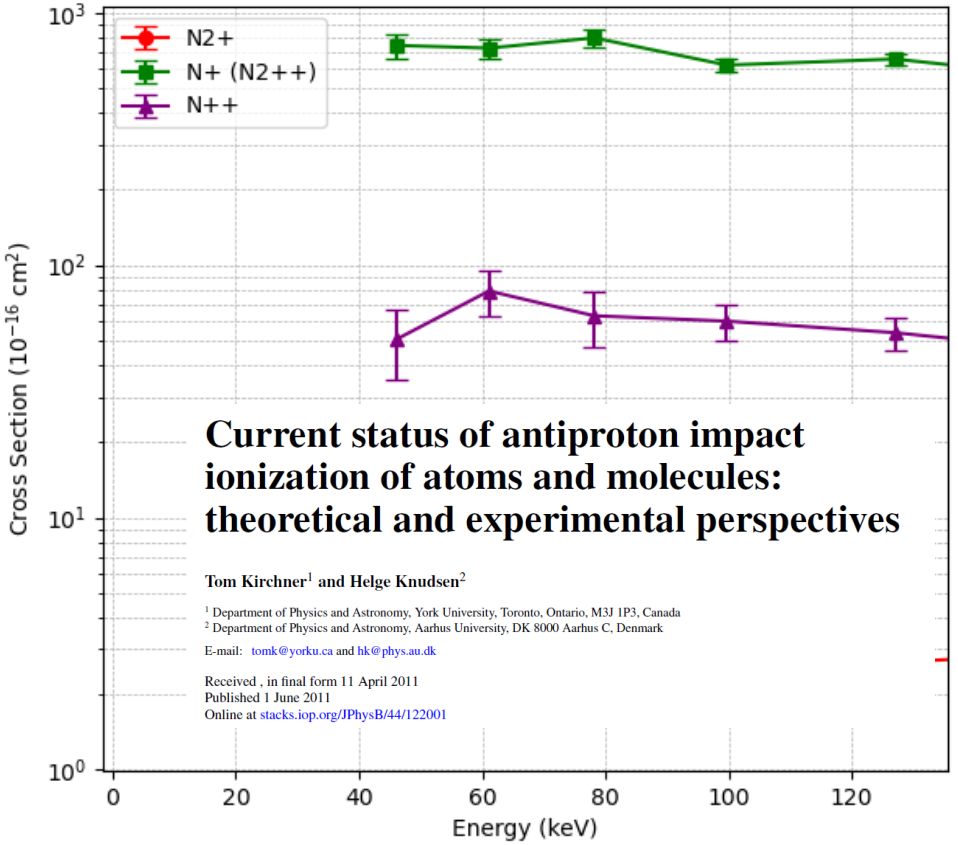




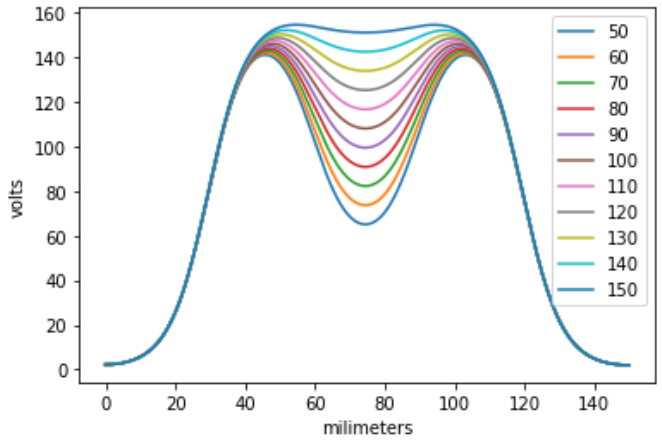
Collisional ionization with antiprotons?

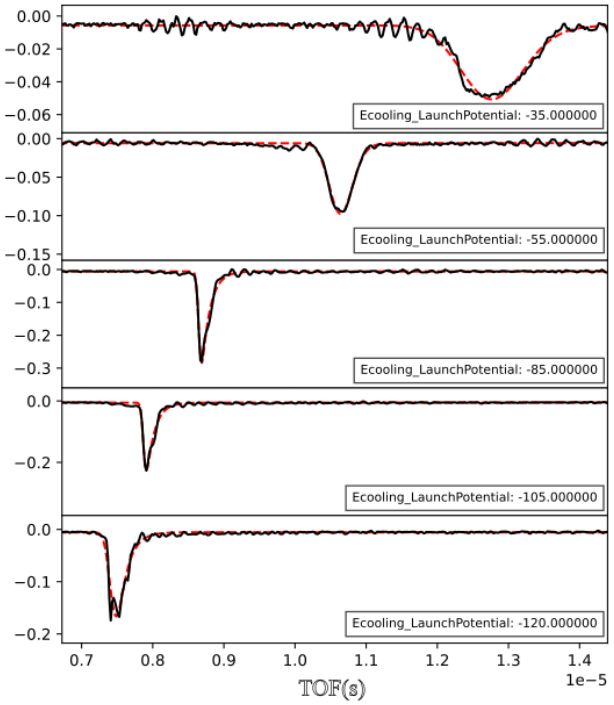
3000 eV is required to form N^{7+} from the N_2 molecule

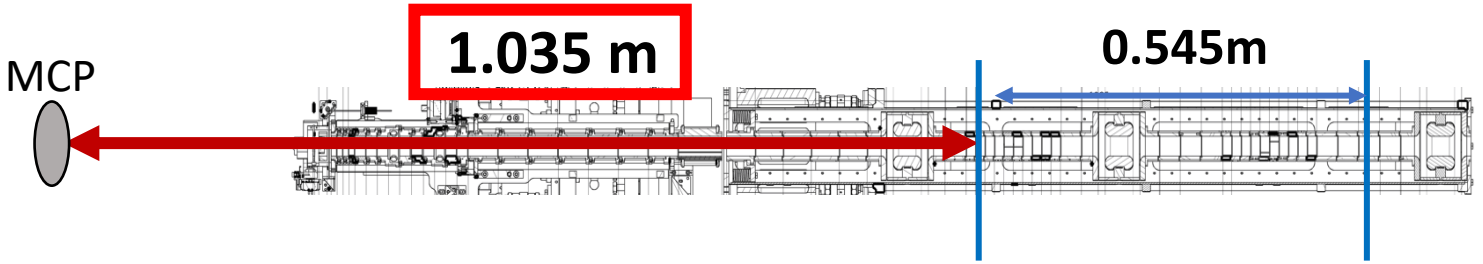


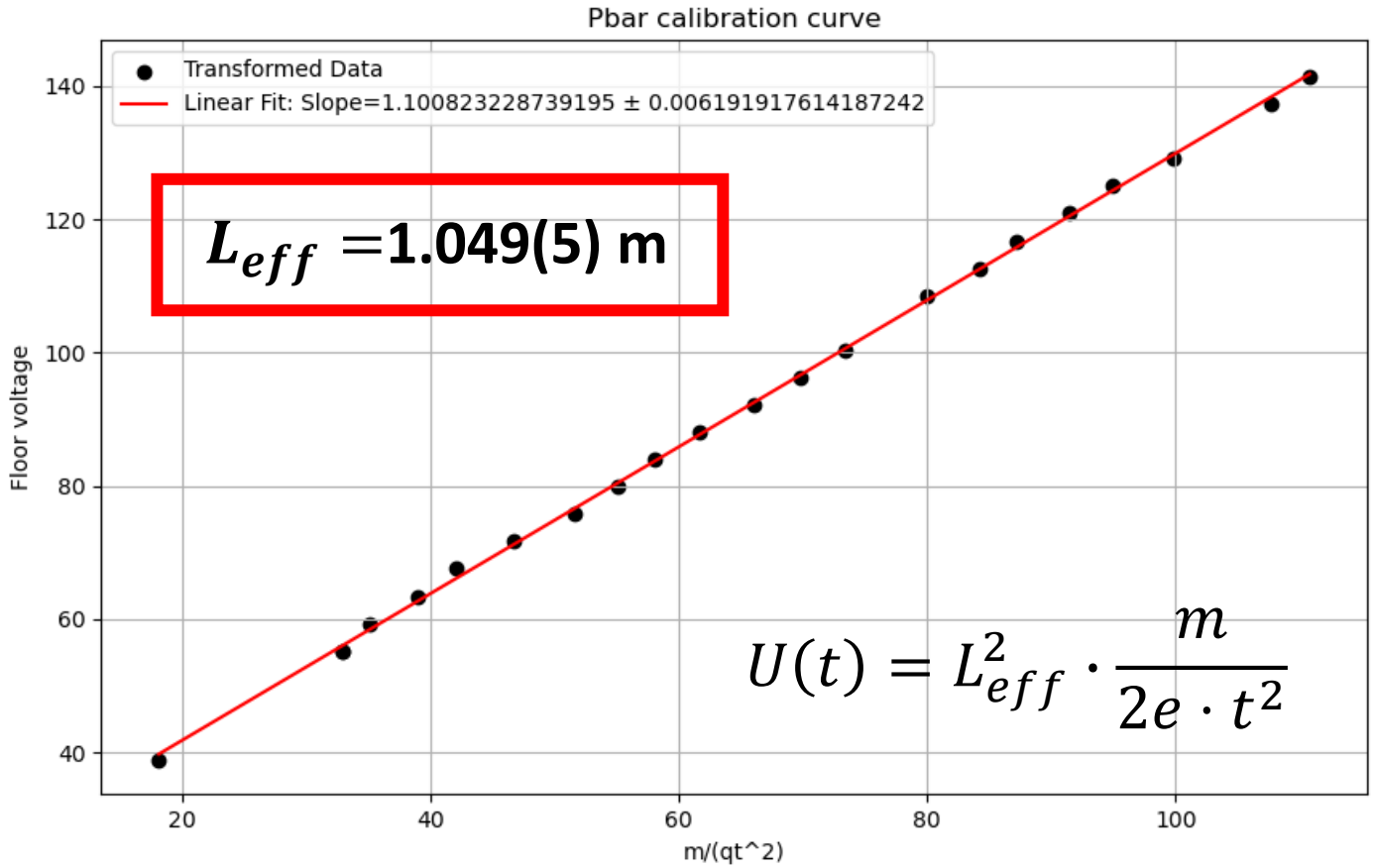


Pbar TOF calibration



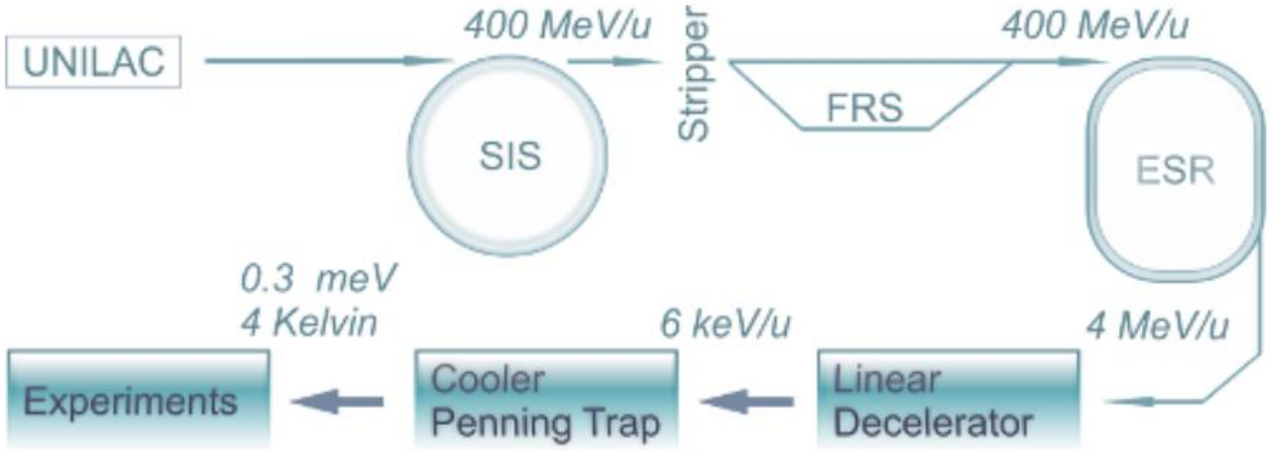






Traditional HCI formation at radioactive beam facilities:

High energy beam through stripper foil:



Electron beam ionization:

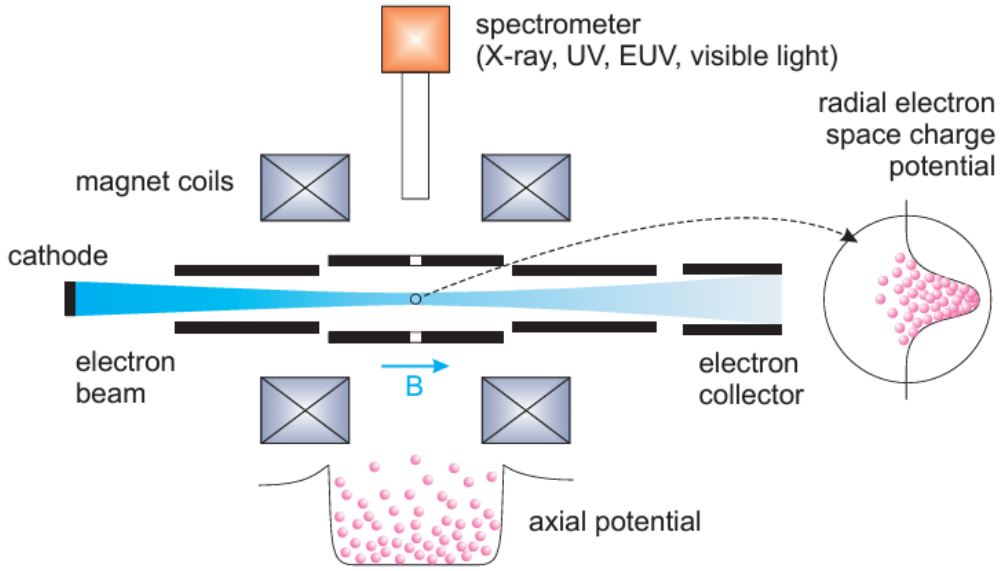
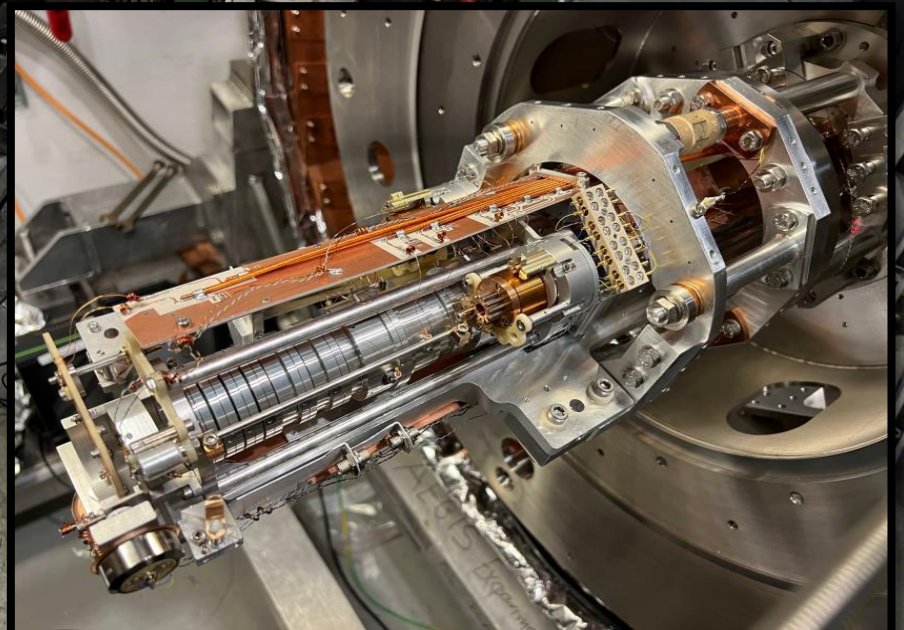


Fig. 2: Principle of operation of an EBIS

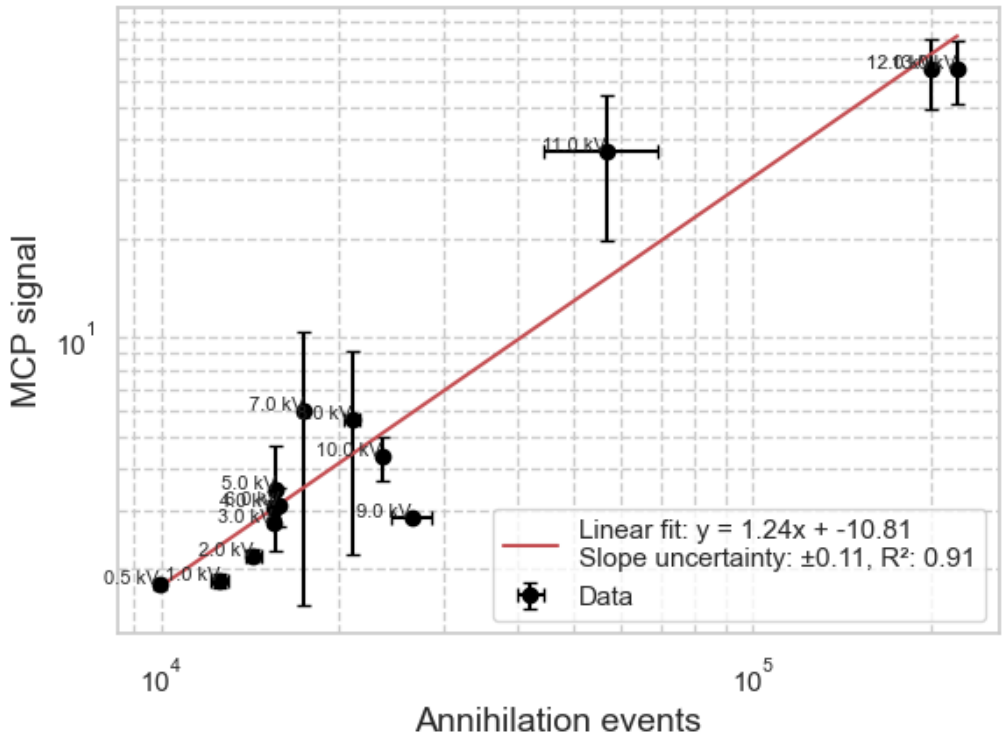
Zschornacka, G., M. Schmidt, and A. Thorn. "Electron beam ion

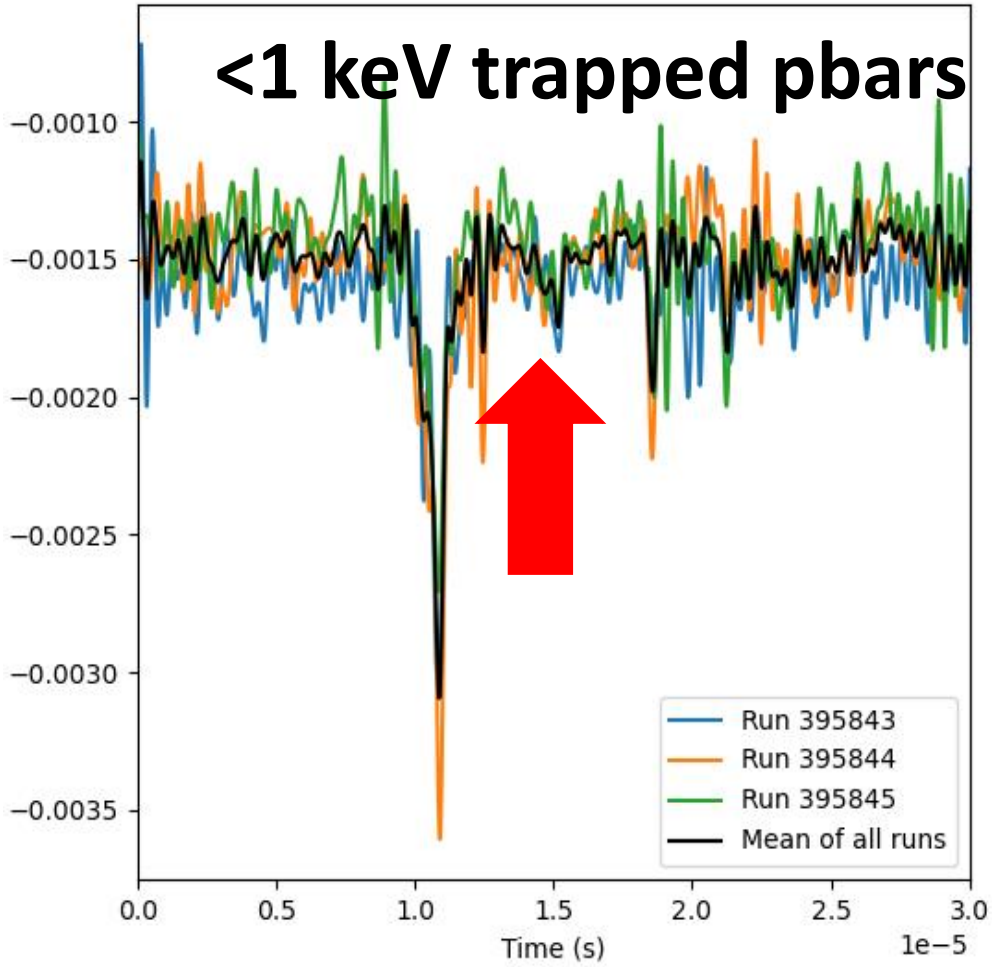
The AEGIS experiment



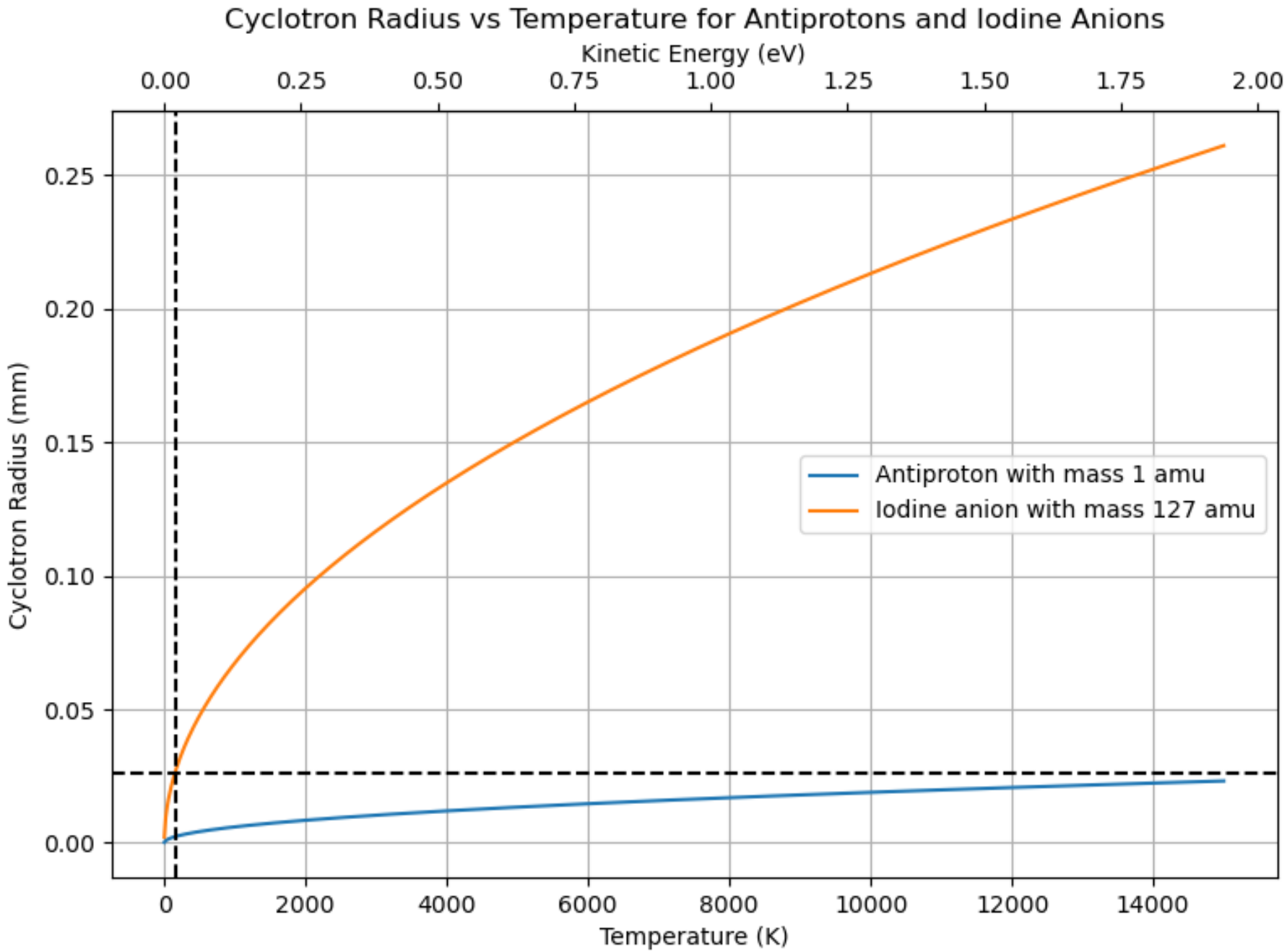
Low energy antiproton interactions

Signal of m/q=2 peak vs annihilation event:

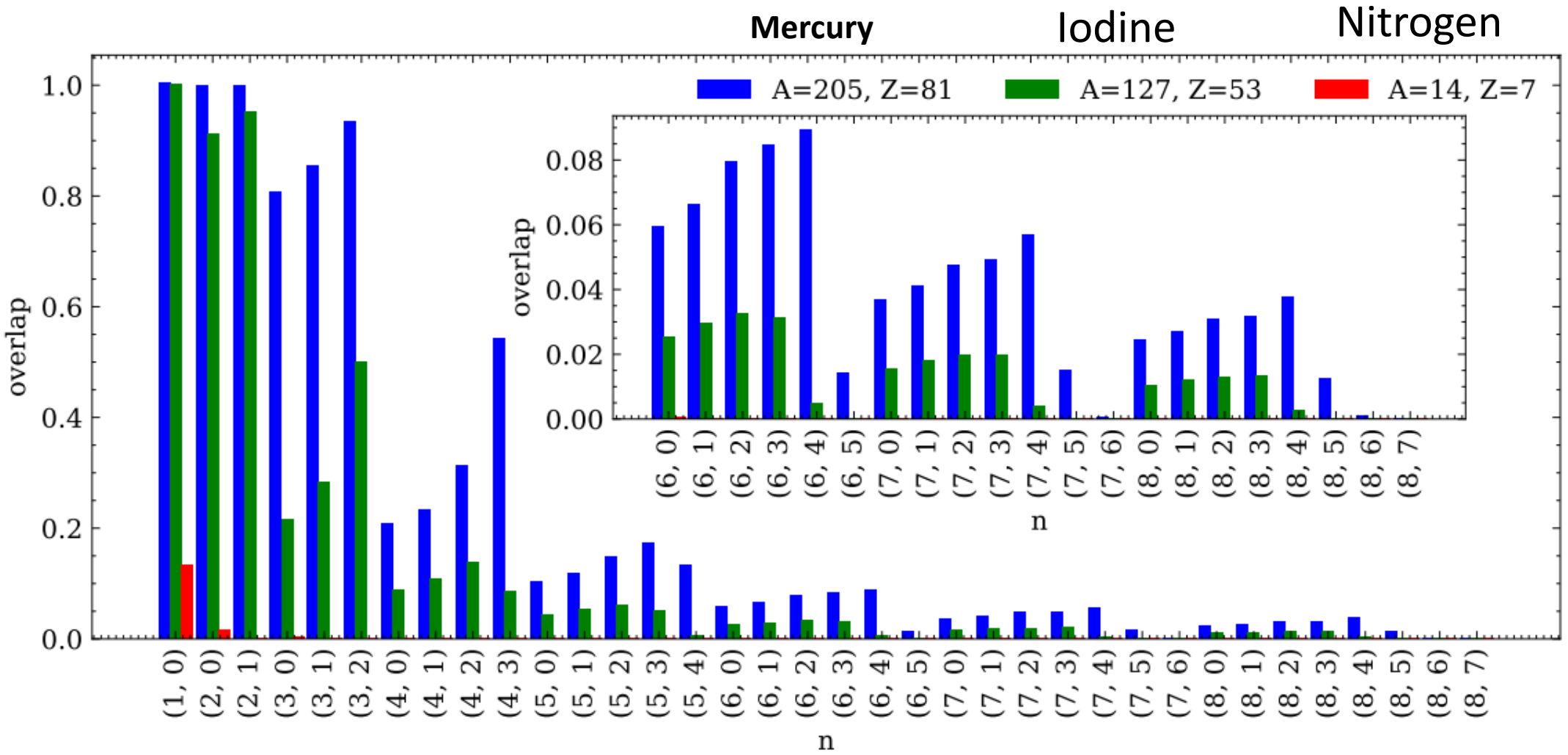




What could result in the formation of m/q=2 from nitrogen?


Cyclotron Radius vs Temperature for Antiprotons and Iodine Anions
Kinetic Energy (eV)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Cyclotron Radius (mm)
0.25
0.20
0.15
0.10
0.05
0.00
Antiproton with mass 1 amu
Iodine anion with mass 127 amu
0
2000
4000
6000
8000
10000
12000
14000
Temperature (K)

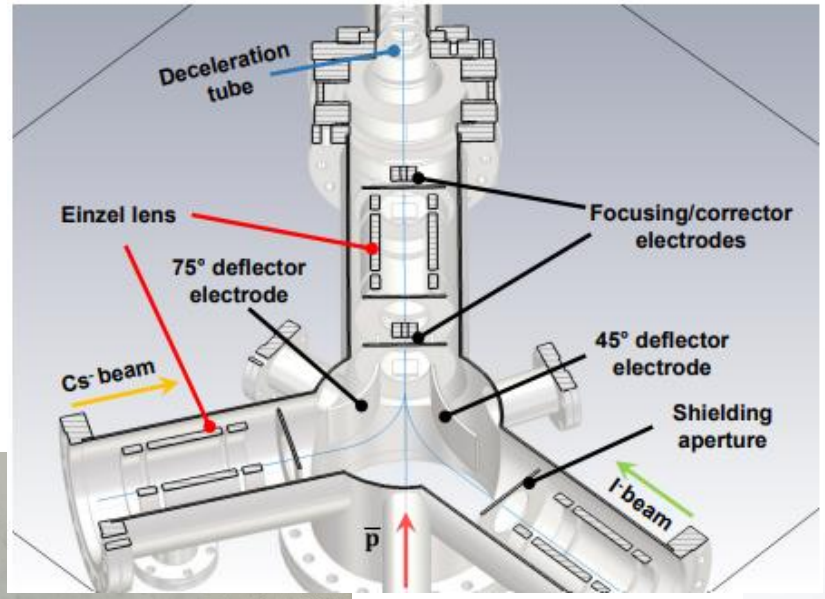
Antiproton overlap with nucleus

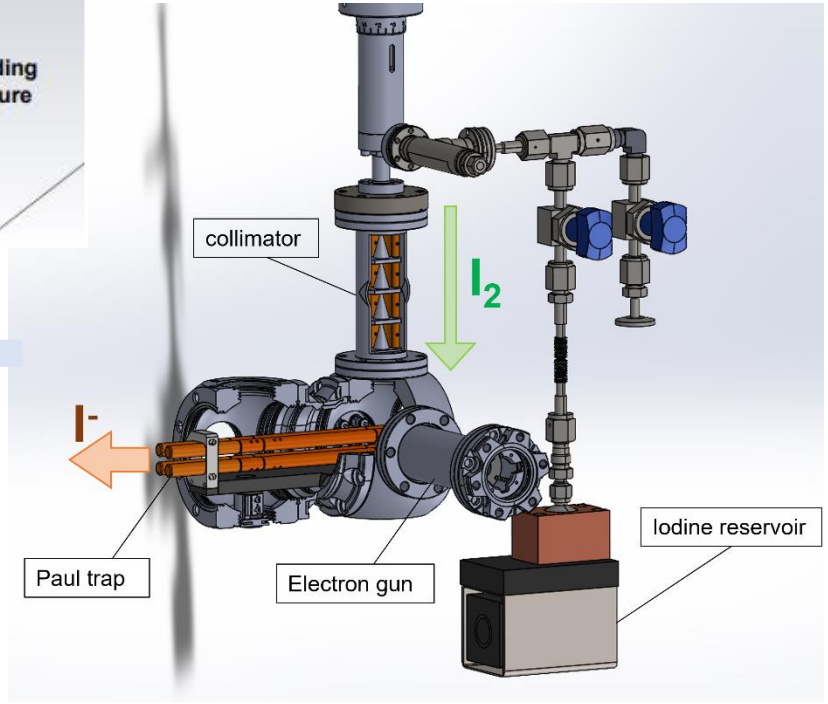


Antiprotonic atoms: setup of the ion injection beamline

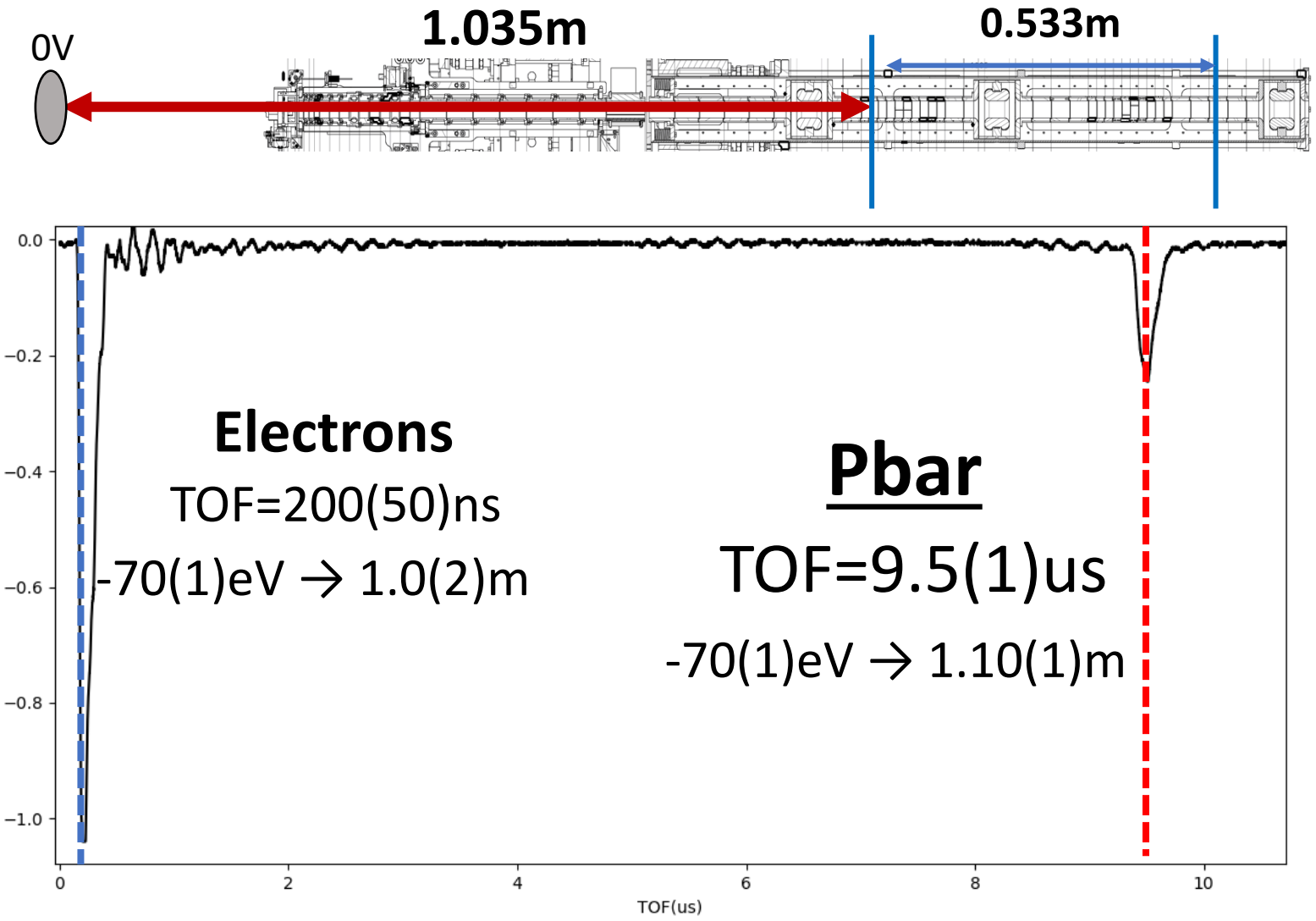
Goal of the R&D: establish the techniques to form antiprotonic bound states.

On track for 2023



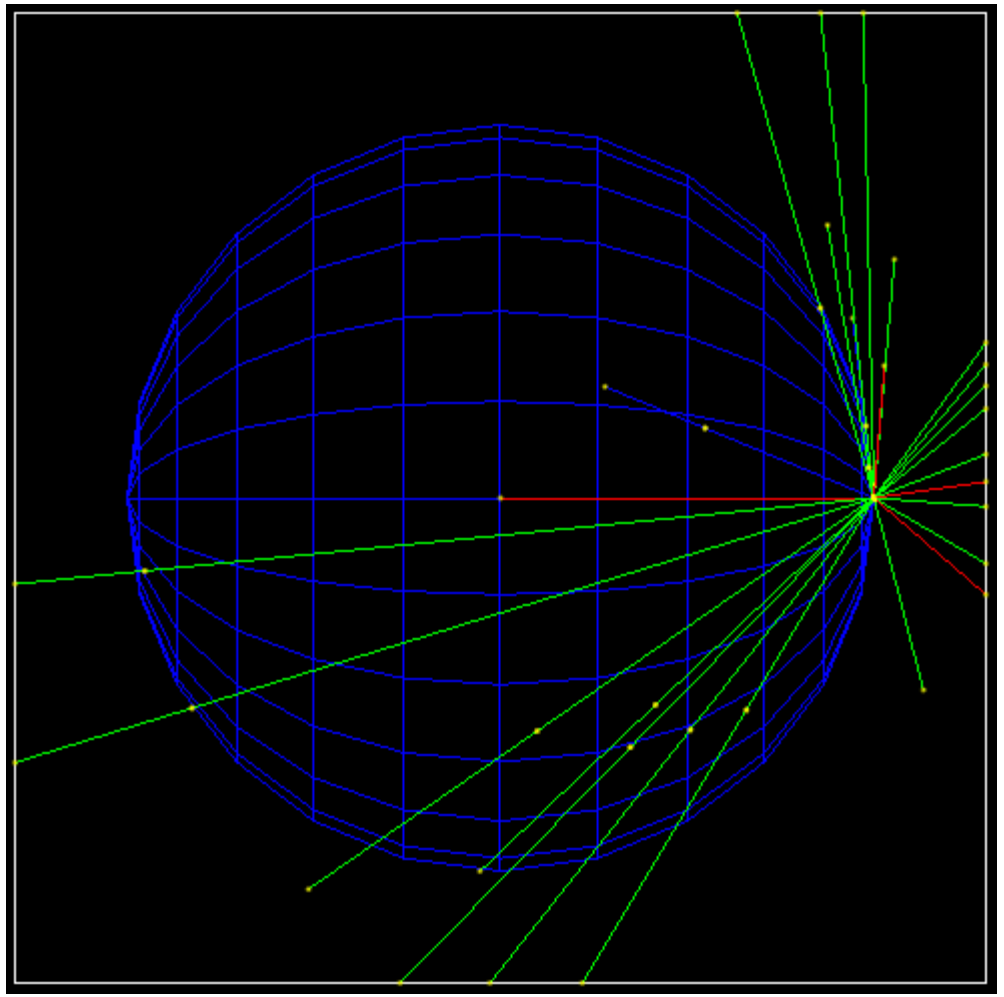


TOF calibration using Pbars and electrons



Simulation – Geant4 set up

- Antiproton is created inside a hollow sphere of 500 nm thickness of target material
- Target defined according to data from a config file (N,Z, density)
  - Simulation ran for different isotopes (over 3000 isotopes)
- 1M antiprotons with E=1 keV
- Physics List:
  - FTFP_BERT_HP



Jakub.zielinski.dokt@pw.edu.pl